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SNC TECHNOLOGIES CORP..
P.O. Box 576
Avon, CT
USA 06001-0576

647-365

Oil Platform Removal Using Engineered Explosive Charges:

In Situ Comparison of Engineered and Bulk Explosive Charges

FINAL REPORT

Prepared by:

Denis Saint-Arnaud (SNC TEC)
Pierre Pelletier (SNC TEC)
William Poe (Explosive Services International)
John Fowler (DRDC Suffield)

Approved by:

Nathalie Maher, Manager, Technologies section

Presented to:

Mr. James Lane
Mineral Management Services, Department of the Interior

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Disclaimer

Executive Summary

Part of the mission of the Minerals Management Service (MMS) of the US Department of the Interior (DOI) is to "manage the mineral resources of the Outer Continental Shelf in an environmentally sound and safe manner". This includes the oil platform decommissioning practices in the Gulf of Mexico. While different methods can be used for this task, Explosive Removal of Offshore Structures (EROS) present some cost advantages on shallow water removals. However, a number of alternative removal technologies exist and are used regularly. EROS is also frequently used in deep water where there are significant risks to divers while inspecting the results of removal operations. The current maximum explosive weight authorized by MMS for explosive structure removal is 50 pounds, which is also the upper limit of charge covered by a generic Endangered Species Act (ESA) consultation. A limit value of 5 pounds was determined to be at a "de minimus" level set by another ESA consultation. The blast characteristics of explosive charges and their impact on wildlife have not been completely assessed. Data on current weight limits have been obtained through modeling and extrapolation, hence the MMS expressed a need to obtain data from actual tests, which could later be used to confirm and validate the weight characteristics.

SNC TEC Corporation team was awarded a contract in the fall of 2001 to develop an explosive charge system that would require less explosive to sever offshore structures through the use of an engineered charge and to obtain data to evaluate its impact on marine life. The aim for the engineered explosive charge total system weight was to be below 10 pounds and, if possible, below 5 pounds. The project team was led by SNC TEC. The team was comprised of Explosive Service International (ESI), Defence Research and Development Canada Suffield (DRDC Suffield) and Sonalysts. The team members were involved in different tasks related to charge development and its set-up on the ESI developed Scorpion™ delivery system as well as the different aspects of testing, including blast measurements during final tests in the Gulf of Mexico.

Following simulation studies, a charge system based on linear-shaped charges was developed to severe oil platform piles of 30" and 48" diameters with wall thickness less than 1.5 inches. The Scorpion™ system was used to hold the charges and position them in the piles. Total explosive charge weights of 4.05 and 6.58 pounds were obtained for the 30" and 48" diameter pipes respectively. In the preliminary tests conducted on submerged pipes in a quarry lake, the Scorpion™ system worked well and the charges successfully severed the two different pile diameters of interest. In the tests against actual structures in the Gulf of Mexico, only 30" piles were available for cutting. It is believed that the Scorpion™ system did not deploy properly leading to improper arrangement of the device in the pile resulting in a reduction of the charges effectiveness and incomplete severing. Additional work would be required in order to solve the problem with the system deployment.

The general conclusions of this study are that the values of peak overpressure, impulse and energy flux density obtained from both the engineered and the bulk charges generally follow the accepted exponential shape when presented as a function of the distance from the blast charge divided by the cube root of the charge weight. These values are also closer to those computed with the Connor similitude equation than those obtained with the ARA model which can be expected based on the method used to obtain the equations and the conservative assumptions used to develop the ARA model. The limit values of 12 psi for the peak overpressure and 182 dB (re 1 μPa^2-sec) for the energy flux density are obtained at half the distance for the 4.05 pounds engineered charge than for the 50 pounds bulk charge. Additional experiments should be performed to confirm more precisely the results obtained.

Abstract

The SNC TEC Corporation team conducted a research program related to the Explosive Removal of Offshore Structures (EROS) and its impact on marine life. This work was performed for a contract awarded by Minerals Management Service (MMS) in the fall of 2001. The major goal of the program was to develop an engineered explosive charge system that would contain less explosive than the standard 50-pound bulk charge to undertake the removal of offshore structures. The targeted total weight of the explosive of the new charge was to be below 10 pounds and, if possible, below 5 pounds. Blast measurements to provide data to compare effects on the environment were also taken during the program.

The Scorpion™ system developed by Explosives Systems International (ESI) was chosen as the system to hold the charges and place them inside the pipes to be severed. The development of the engineered charges was based on the advantages of the shaped charge. Numerical modeling and experimental validation were performed on different types of linear-shaped charges. The computer simulation results were used to obtain the optimal dimensions for the linear shaped charge design to be used. These dimensions were found to be close to those of a commercial charge manufactured by Accurate Energetics. A sturdy waterproof casing was designed to hold the complete charge system to ensure adequate functioning and fit on the Scorpion™ . These charges were designed and manufactured for the removal of 30" and 48" diameter piles. Although the design of charges for the removal of 24" piles has been completed, they were not manufactured.

Testing of the design, first at Defence Research and Development Canada (DRDC) Suffield and then at the ESI test range, led to the final development of the charge design containing total explosive charge weights of 4.05 and 6.58 pounds for the 30" and 48" diameter pipes respectively. Tests were then conducted on submerged pipes in a quarry lake to demonstrate the ability of the engineered charges mounted on the Scorpion™ to sever both diameters of pipes and to test the blast measurement array. Good results from all the preliminary tests was followed by validation testing of the system in the Gulf of Mexico against actual structures made of 30" piles. The results showed incomplete severing of the pipes with about two thirds of the pipe circumference uncut. Evidence indicates that an imperfect deployment of the Scorpion™ may be the cause. Additional work will be required to solve the problem with the deployment system.

Measured peak blast overpressure values obtained using the experimentally recorded pressure curves from two 50 pounds bulk charge and the engineered charge were studied along with the impulse and the energy flux density computed from those pressure curves. This data was reviewed as a function of the distance from the charge divided by the cube root of the charge weight. While general tendency of the data for both types of charge was to follow the generally accepted exponential shape of similitude equations, this data was relatively scattered, as indicated by regression coefficients (R^2) between 0.40 and 0.90. The measured data did not also always follow the expected pressure reduction with the distance from the blast point. For both types of charges, the measured data is closer to the computed data from Connor study similitude equations compared to the Advanced Research Associates (ARA) model particularly for impulse and energy flux density. This can be expected since the ARA model was developed from theoretical conservative assumptions while the Connor similitude equations were derived from experimental data. The peak overpressure data of the engineered charge were generally lower than the bulk charge data. The computed distance to obtain the 12 psi peak blast overpressure and 182 dB (re 1 μPa^2-sec) energy flux density with the engineered charge is about half that obtained with the bulk charge. This corresponds closely to the ratio of 2.31 for the cube root of the bulk charge weight and engineering charge weight.

List of Abbreviation

ALE	Arbitrary Lagrangian-Eulerian
ARA	Advanced Research Associates
CD	Charge width for linear shaped charge and charge diameter for axisymmetric shaped charge
Composition B	Explosive formulation made of 59.5% RDX, 39.5% TNT and 1% wax
Composition C4	Explosive formulation made of 91% RDX in 9% polyisobutylene binder
CTD	Conductivity, temperature and depth
DOI	Department of the Interior
DRDC-S or DRDC Suffield	Defence Research and Development Canada - Suffield
EROS	Explosive Removal of Offshore Structures
ESA	Endangered Species Act
ESI	Explosive Systems International
GOM	Gulf of Mexico
HSS	Hollow Structural Section
LSTC	Livermore Software Technology Corporation
LSC	Linear Shaped Charge
MMS	Mineral Management Services
NMFS	National Marine Fisheries Service
nonel	non-electric
PETN	Pentaerythritol tetranitramine explosive
PVC	Polyvinyl chloride
RDX	cyclotrimethylenetrinitramine or cyclonite explosive (abbreviation stands for Research Department Explosive)
SNC TEC	SNC Technologies Inc.
SNC TEC Corp.	SNC TEC Corporation; American branch of SNC TEC

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1.0 - INTRODUCTION

Part of the mission of the Minerals Management Service (MMS) of the US Department of the Interior (DOI) is to "manage the mineral resources of the Outer Continental Shelf in an environmentally sound and safe manner". Current oil platform decommissioning practices in the Gulf of Mexico include explosive and non-explosive severing technologies. Most explosive severings use "bulk" charges to section the structures being removed. The current maximum explosive weight authorized by MMS for explosive structure removal is 50 pounds; the upper limit of charge permitted by a generic Endangered Species Act (ESA) consultation. The lower limit of >5 pounds is determined to be a "de minimus" level set by another ESA consultation. The blast characteristics of explosive charges and their impact on wildlife has not been completely assessed. Data on current weight limits has been obtained through extrapolation, hence the MMS expressed a need to obtain data from actual tests which could be later used to confirm and validate the weight characteristics.

. SNC TEC Corporation was awarded a contract in the fall of 2001 to perform in situ comparison of an engineered charge, to be developed in this contract, with the standard bulk charge and their impact on marine life when used for the Explosive Removals of Offshore Structures (EROS) The general goal of this study was to better use the energy available from the explosive charges used for oil platform disposal. This would allow the use of a smaller quantity of energetic material to perform the same work thereby reducing the impact on the environment. To put these charges in place for the severing of pipes, the method considered was the use of the Scorpion™ system developed by Explosive Service International (ESI), which is described in Section 2.0 of this report. Part of the design work therefore involved the study of the charges set-up and the development of an initiation method to fit this delivery system to effectively remove the structures piles found in the Gulf of Mexico. The aim was for a total explosive weight mounted on the Scorpion™ lower than the "Generic consultation limit" which requires a less rigorous approval process. This meant an explosive weight of less than ten pounds and, if possible, less than five pounds. At the beginning of the contract, it was considered to study two concepts of engineered charges to sever the pipes; one based on fracture tape and one based on linear shaped charge. The fracture tape resembles shaped charges but it is flexible, contains less explosive and although it has been proven successful in some systems which were set in place by a diver[1], it must be in perfect contact with the surface of the pile to section to obtain the required cut. The principle of operation is the transfer of the shockwave to crack the pipe wall. The fact that the charges in the system would not be at the same level due to the nature of the Scorpion™ design, it was questioned if a continuous cut could be obtained. The use of such a system based on this type of charge was concluded as not likely to be sufficiently reliable and it was therefore decided early in the program to limit the work to linear shaped charge because this system was

[1] Poe, W.T., *Method and Apparatus for Removing Abandoned Offshore Fixed Platform,* US Patent 6,230,627 B1, 15 May 2001.

viewed as having more capabilities for development of the required engineered charge. This report will therefore address this type of charge only. At the beginning of the contract, the possible option to compare the environmental impacts of the engineered charge with the bulk charge by measuring the blast pressure was considered and eventually exercised as encouraging results were obtained during the charge development and preliminary testing tasks.

The project team was led by SNC TEC, who was responsible for the contract management, involved in the design of charges, as well as its manufacturing (certain parts were made per SNC TEC and others subcontracted). DRDC Suffield organization was responsible for the charge design and the preliminary tests. ESI was responsible for the full-scale tests in Louisiana including the supply of the Scorpion™, mounting of the engineered charges, obtaining the permits and the coordination of logistics. Some preliminary tests prior to the tests in the Gulf of Mexico were performed under ESI. When the contract option was exercised, Sonalysts joined the team to take the measurements and make comparisons of blast effects.

The tasks involved in this program were as follows:

- Task 1: Development of an engineered charge design using computer simulation;
- Task 2: Development of the explosive charge casing;
- Task 3: Manufacture and filling of charges along with casing manufacturing;
- Task 4: Preliminary testing of the concept at DRDC Suffield;
- Task 5: Design review, optimization and validation;
- Task 6: Manufacture of the final charge design and testing of the charges;
- Task 7: Final testing of the charge system, first in quarry lake to validate the final design and then in the Gulf of Mexico against existing structures;
- Option (executed during Task 7): Blast measurements and comparison of the engineered charges with bulk charges;
- Task 8: Final report.

This final report will present all the work performed during the course of this program in chronological order to show the reader how the charge concept evolved up to its final testing in the Gulf of Mexico. The Scorpion™ general design will first be presented in order to provide some information on the set-up of the charges in this system. This will be followed by the review of the first concepts tested and the methods, both numerical simulations and experimental, used to develop them. Discussion of the preliminary tests performed at DRDC Suffield to check the concept and their conclusions will then follow. This testing resulted in modifications to the design, which will be discussed in the following section along with testing of these modifications. This report will be concluded by presentation of the results of testing of the final concept against simulated piles in a quarry lake and then on actual platform piles in the Gulf of Mexico following a review of the final charge design as manufactured for those final tests. This will include the discussion of the blast measurement method and results.

2.0 - SCORPION™ DELIVERY SYSTEM

When the project team was created to prepare the project proposal, it was decided to develop the explosive charge system to fit on the Scorpion™ system developed by ESI. This system has been used successfully with other charges and it was seen as having a very good potential to deliver the engineered charges to the sectioning point without the use of a diver. In this section, we will discuss the Scorpion™ features.

The Scorpion™ consists of a circular charge holder of adjustable diameter supported by a spring loaded frame. In the collapsed (reduced diameter) mode, the device may be leveled inside the pile, once it has reached the desired depth, the spring loaded frame is released pushing the circular charge holder hard against the inside diameter of the pile. A first design of the Scorpion™ was patented in May 2001[1]. Figure 2.1 shows side and top views of this first Scorpion™ design in the collapsed configuration that enables its insertion in pipes even if the pipes are at some angle. When the Scorpion™ is lowered at the required level, a detonator (#108 in the figure) sections the cable (#109 in the figure) that was retaining the system in the collapsed position. The action of the upper and lower springs (#111 and 112) pushes the charges outwards in the open position of the Scorpion™. Both side and top views of the Scorpion™ in the deployed configuration are shown in Figure 2.2.

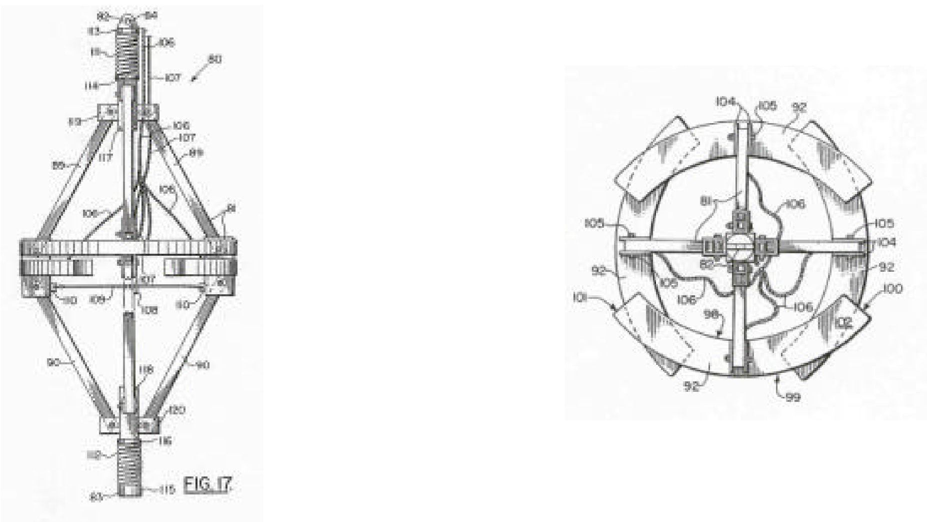


Figure 2.1 - Scorpion™ in collapsed configuration – Side and top views

[1] Poe, W.T., *Method and Apparatus for Removing Abandoned Offshore Fixed Platform*, US Patent 6,230,627 B1, 15 May 2001.

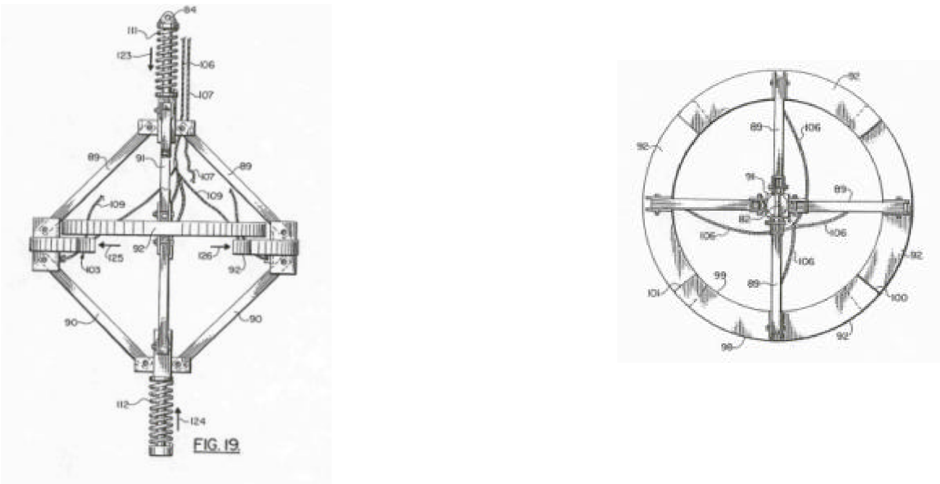


Figure 2.2 - Scorpion™ in deployed configuration – Side and top views

A picture of the original Scorpion™ configuration with one section removed to show the arrangement of the charges is presented in Figure 2.3.

Figure 2.3 - Picture of the original Scorpion™ system with the front charge removed

During the course of the program, ESI developed an improved version of the Scorpion™ named Scorpion-2 . The idea behind this design was to obtain a simpler and more robust arrangement for charges deployment. The springs are now set at the charge level rather than at the top and bottom. A new feature was the inclusion of top and bottom rings to protect the charge assembly when lowering the Scorpion™ in the pipe to sever.

Pictures of the Scorpion™ are shown in Figure 2.4 to Figure 2.6. The first one shows the Scorpion™ in the collapsed position with the charges in place after the springs were tightened.

The metal wire used to keep the arrangement in the collapsed position is indicated by the black arrow. Figure 2.5 shows the initiation system and the detonation cord set in place with the Scorpion™ ready to be lowered in the pipe. The left side picture is a top view with the top and bottom positioning rings not in place. The picture on the right side is a side view of the system with the bottom-positioning ring in place. The pictures presented in Figure 2.6 show the Scorpion™ lowered in a pipe with the positioning rings not in place. The left side picture shows the system in the collapsed configuration while the right side shows it in the deployed configuration.

Holding wire

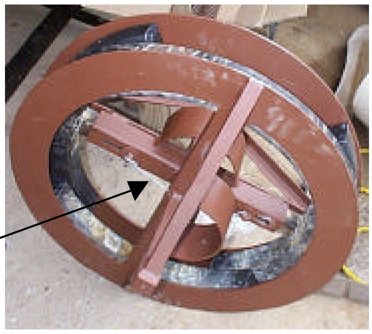


Figure 2.4 - Scorpion™ with the charges in place

Figure 2.5 - Scorpion™ with the initiation systems and detonation cords in place

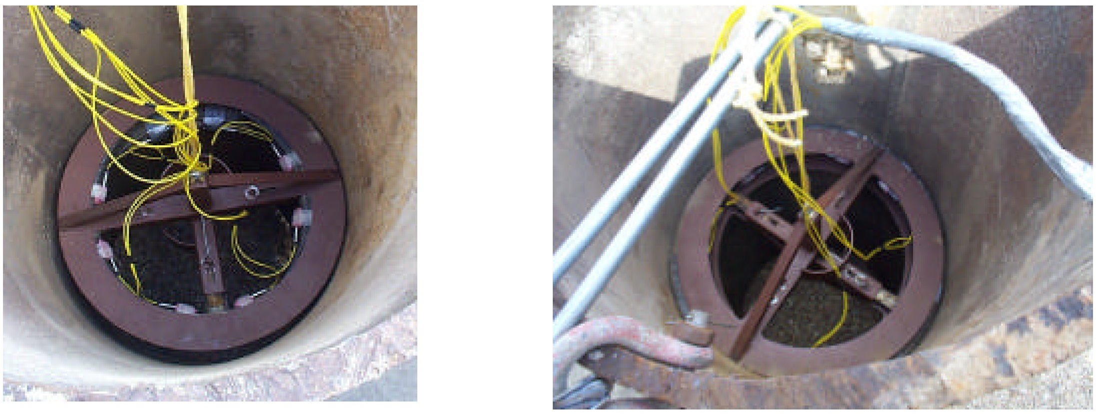


Figure 2.6 - Scorpion™ lowered in a pipe

3.0 - ENGINEERED CHARGE DESIGN – SHAPED CHARGE

When considering an explosive charge design to replace the bulk charge system with an engineered charge, different systems such as the fracture tape and the shaped charges were reviewed for the proposal. After briefly considering fracture tape (as mentioned in the introduction) efforts were concentrated on the linear shaped charge concept. The engineered charge to be designed to sever the oil platform piles is made of a linear shaped charge (LSC) enclosed in a waterproof casing. In this section, we will present the shaped charge design.

3.1 Shaped charge principle

The shaped charge was selected over other types of explosive charges because this type of charge uses the energy of the explosive in a very efficient manner therefore less explosive would be needed to accomplish the same task. The shaped charge effect also known as the Munroe effect is based on the fact that a cavity formed in an explosive charge at the extremity away from the detonation point produces an increase of penetration in a target material. If the cavity is lined with a thin layer of ductile material, such as pure copper, the penetration capability is increased. Setting of a distance between the bottom of the charge cavity and the target can further enhance the penetration. This stand-off distance, is typically three to five time the charge diameter for an axisymmetric charge.

The penetration capability of the shaped charge comes from the formation of a concentrated jet of material from the liner. The high pressure developed by the explosive reaction produces a jet travelling at very high velocity, typically 3 to 15 km/s (10000 to 50000 ft/s). Ductile materials, such as pure metals, are used to produce shaped charge because the formed jet can extend more before breaking and produce more penetration at high stand-offs. Denser materials produce higher penetration because the jet material is less eroded by the target.

So far, axisymmetric or cylindrical charge has been discussed, but the same effect can be obtained with linear charges although the sectioning or penetration ability is lower because the jet velocity is typically lower. This happens because the concentration of the explosive energy is produced along a line rather than around a point.

The definitions of the terms that will be used in this report will be presented here to ensure good comprehension and avoid confusion. The current names of a shaped charge parts are the explosive charge, the liner and the casing. The liner is the ductile metallic part of the shaped charge which is deformed by the explosive to form the jet which penetrate the target. The casing refers to structural material surrounding the explosive which is not part of the liner and whose purpose is to produce explosive confinement and improve the charge performance by containing the gasses and energy produced by the explosive, up to a certain time, and direct it towards the liner. The complete linear charge will have to be contained in a casing to install it in the

Scorpion™ system and keep the cavity under the liner free of water. To differentiate between those two casings, it was decided to use in this report the term tamping to refer to the structural material surrounding the explosive; this term being used currently by scientist working in this field to refer to the shaped charge casing.

3.2 Numerical modeling

The first step of the program was to perform a study of linear shaped charge (LSC) using computer simulation with a hydrocode to select the optimal dimensions of the explosive charge. This work was partly subcontracted to Defence Research and Development Canada (DRDC) Suffield in Alberta, Canada whose objective was to run a parametric study to obtain these optimal values for the charges that were then to be manufactured by SNC TEC.

A review of LSC design led to the selection of the following range of values to start the studies based on DRDC Suffield experience with LSC. The LSC design would require a charge width of 1.5 - 1.9", an included angle of 75-100° and should have an optimum stand-off of approximately 1". The liner thickness to charge diameter ratio for LSC should range from 4 to 6% for optimal performance. The core loading required to penetrate 2", as indicated in the literature and manufacturer catalogues, is typically 8-10 g/cm (3650 – 4725 grains/foot). It was believed that improvements might be achieved by modifying tamping confinement and the initiation concept. It has been shown that increasing confinement in axisymmetric charges allows the base of the liner to make a larger contribution to the jet and hence improve penetrating ability.

3.2.1 Experimental validation testing

During the modeling and simulation phase (see next section), experimental validation of the results was conducted to confirm the validity of the simulations. Initial experimental testing was performed on sheathed copper shaped charges filled with RDX explosive. Those were readily available at DRDC Suffield commercial charges manufactured by GOEX. These linear shaped charges had a charge width of 1.25 inches, a core loading of 6.783 g/cm (3190 grains/foot), and a liner angle of 75 degrees. The six-inch long charges used were all fired at a one-inch standoff from a two inch steel plate. Some results obtained with different initiation arrangements are presented in Figure 3.1 and Figure 3.2.

Figure 3.1 - Penetration of center initiated charge

Figure 3.2 - Penetration of a charge initiated 1.25 inch from the left end of the charge

The measured data indicated that the penetration at the impact face was the same length as the shaped charge.

To check the effect of different parameters on the charge design, charges containing liners formed with a folding brake press were produced for the program. These charges were tested against a water backed steel plate to better represent field conditions. It was considered that water and soil backing would result in less spall from the rear of the target plate as compared to an air-backed target which could therefore reduce the thickness of steel sectioned by the charge. The typical charge manufactured at DRDC Suffield in illustrated in Figure 3.3. The explosive chosen for this work was C4 explosive because it could easily be molded by hand in different charge designs.

Figure 3.3 – Experimental validation charge

The twelve-inch charge has a rather small cavity for the explosive which, combined with its length, led to difficulties in packing the C4 explosive. The presence of air gaps in the charge impedes the creation of a good jet which does not recover as seen from the limited penetration observed in the left side of Figure 3.4 below.

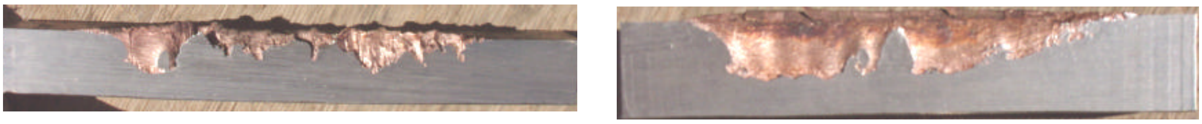


Figure 3.4 – Penetration results of 12 inches and 8 inches validation charges (side view after sectioning)

Shortening the charge to eight inches allowed for the charge to be packed more easily and resulted in improved performance as shown in the right side of Figure 3.4.

The insufficient accuracy and precision in liners geometries produced by folding brake press does not permit to check the actual effect of the parameter values. Commercial charges with the required precision would have been prohibitively expensive to produce with varied geometries. It was decided to produce the liners by machining two plates to the appropriate geometry and laying them up in a jig to locate them while the plates were soldered together along the apex of the liner. Machining the liner allowed a higher precision charge with more accurate dimensions which resulted in better performance as illustrated in Figure 3.5.

Figure 3.5 – Penetration results of improved 8 inches validation charge

Initial experimental testing performed on sheathed copper shaped charges filled with RDX explosive required 3 to 4 inches to run-up. It is interesting to note that the machined design with C-4 required half of this distance to achieve its maximum penetration. A flash X-ray photograph looking down the length of the charge as it detonates is shown below (Figure 3.6). The jet can be seen exiting from the bottom of the charge and the end of the charge that has yet to detonate is seen as a slightly lighter shadow. The velocity of the jet tip was measured to be 3.26 km/s. This data along with other measured values were used to validate the numerical modeling.

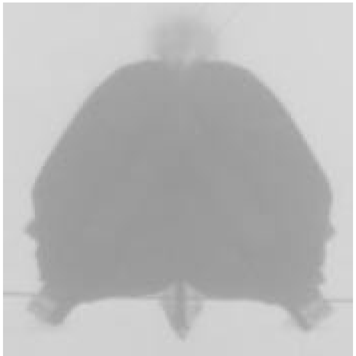


Figure 3.6 – Flash x-ray of the functioning of the 8 inches validation charge

3.2.2 Hydrocode simulation

The term "hydrocode" is used to name a finite element or finite difference software developed to simulate large non-linear dynamic deformation in materials. This type of computer program has been used typically for the last thirty years to simulate, among other things, systems involving explosive charges deformation of metal and high-speed projectile penetrations. Along with the conservation equations (mass, momentum, energy and entropy), these codes require a complete definition of the materials involved by a stress-strain relation (constitutive model), equation of state, failure criterion and post-failure model.

The simulation work performed by both DRDC Suffield and SNC TEC was done using LS DYNA 3D hydrocode[2]. This hydrocode is of the finite element type. One advantage of this code is the capability to use lagrangian, eulerian or a hybrid of both types of mesh description (arbitrary lagrangian-eulerian or ALE). Each of these mesh description presents advantages and having all of them enables to choose the adequate one depending what we wanted to achieve in the different parts proved to be an advantage in this project.

[2] *LS-DYNA – Keyword User's Manual Version 970*, Livermore Software Technology Corporation, April 2003

Following the analysis with the hydrocode, the resulting data can be analyzed using a post-processor to evaluate displacements, velocities, accelerations, deformed geometry of bodies, stress and strain produced, reaction forces, energy, etc. This data is useful to verify the quality of the results, perform comparison between models and ultimately perform the parametric study.

The first step was to develop the geometry of the models for the originally proposed charge and case design arrangements including the meshing. The casing design work will be discussed in more details in Section 4.0 of this report. Two typical linear shaped charge design models used in the parametric study are illustrated in Figure 3.7.

Figure 3.7 - Typical meshes for parametric design with square and boat-tailed design

Some 2D model simulation was performed using adaptive re-meshing techniques to follow the high deformation of the material. This was completed by eulerian simulations to perform numerical parametric studies for linear charge trade-off studies. Two models used in the parametric study computed with the eulerian meshing are illustrated in Figure 3.8.

Figure 3.8 - Euler models of a 110-degree and a 75-degree charge

The results obtained during the parametric studies were put in graphs. These results were used to determine the optimal charge design presented in the next section.

3.2.3 DRDC Suffield simulation work conclusions

The parametric studies performed by DRDC Suffield from computer simulations validated by field trials led to the following conclusions regarding the optimum design profile. Figure 3.9

shows the definition of the parameters outlined in Table 3.1. The charge tamping is illustrated in yellow, the explosive charge in blue and the liner in red. During the simulation at DRDC Suffield, there was differentiation between the tamping at the back and on the sides or wall as indicated in the figure.

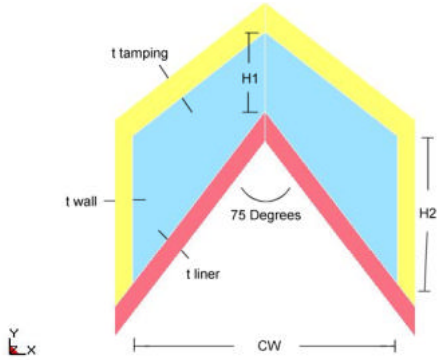


Figure 3.9 – Linear shaped charge design profile

Table 3.1 - Optimal values for linear shaped charge design

Penetration [inch]	CW [inch]	H1 [cm]	H2 [cm]	t tamping [cm]	C [g/cm]
1.5	1.25	0.948	1.776	0.283	6.8
2.0	1.625	1.316	2.527	0.292	12.5

Note: t wall = t liner =0.218cm for both cases

3.3 Additional testing

Following the simulations done by DRDC Suffield, some tests were done on the optimal design to check the results obtained and the ability to sever a pile.

Since the dimensions of the piles originally identified as the most likely target to be encountered in the Gulf of Mexico, and therefore those considered for the final testing in Task 7, were 48"ø diameter with 1.5" thickness, preliminary testing was done on a pipe corresponding to these dimensions and made of the same steel. Using similar type of targets as those to be used for final testing improved our knowledge of the pipe material and its behavior.

The pile material was tested with several charges to determine the minimum amount of explosive required to sever the 48-inch pipe. The test set-up is shown in Figure 3.10. The pipe was water backed to provide a more realistic environment.

Figure 3.10 - Experimental set-up for testing charges against pile

The charges were detonated and the penetration of the pipe was determined. The resulting cuts obtained on the pipe are illustrated in Figure 3.11.

Figure 3.11 - Pile following charge trial

The 48" diameter, 1.5", pipe was cut most efficiently by the 75° charge. Difficulties arose again related to the hand packing of the C4 charges resulting in inconsistent performance. This problem was eventually eliminated by the use of cast or pressed charges in the final design. The core loading required to cut the 1.5" pipe is consistent with calculated values presented in Table 3.1.

3.4 Review of linear shaped charge design

At the end of the work performed by DRDC Suffield and presented above, the results were discussed between SNC TEC and DRDC Suffield in view of manufacturing the explosive charges for further testing in the actual configuration. Some additional questions regarding the charge size to be able to cut the pipes were raised from the results. This led to a more complete literature review on linear shaped charges (LSC) to obtain data and analytical design equations in order to get an idea on the required charges.

The original work plan and the goal of the study for DRDC Suffield was to consider the complete development of a LSC filled with a melt-cast explosive such as composition B. Some designs were proposed by DRDC Suffield using the data presented in Table 3.1 but the manufacturing would have required many operations with a detrimental effect on the cost of the final charges. It was therefore decided to review available commercial LSC to see if products meeting the values determined by the parametric study were available.

While the work had been first done considering a 48" pipe, it was also decided to work on 36", which was also believed, from what we were told, to be a common diameter to produce oil platform legs.

3.4.1 Additional design considerations

The dimensions of pipes to section considered in the computations were inside diameters of 36 and 48" with wall thickness of 1.5 and 2". In addition to these thickness, we looked at cases in which an additional 0.25" representing the thickness of the casing put around the charge to produce the stand-off and ensure a space free of water below the liner was added to the pipe thickness. This subject will discussed in Section 4.0 of this report.

An important value to consider is the length of the charge so the required size was computed. It was considered that the diameter of the pipe refers to the inside diameter. With the Scorpion™ design, this length would be made of four sections that would have respectively 28.274" for the 36" pipe and 37.699" for the 48" pipe. Each of these sections subtends an angle of 90°. This angle does not present a problem with the pressed commercial LSC but can not be used to fill the charges with composition B explosive. This type of melt-pour explosive requires casting in already curved charge hardware and the casting cannot be done without trapping air. Based on our experience with this type of explosive, a 45° subtended angle appeared to be the maximum angle that would be feasible to obtain a good quality charge. This means that two sections of charge would be required on each leg of the Scorpion™ and that the charge length would be about 14" for the 36" pipe and 19" for the 48" pipe.

3.4.2 Linear Shaped Charge (LSC) analytical computations

The formulas used to compute the data for the LSC were taken from the book "Introduction to the Technology of Explosives"[3]. It is mentioned in that reference that after you penetrate to a certain level of the thickness of the target, the rest will crack by itself. Obviously, this depends on the material and the arrangement to be sectioned and may not apply because there is pressure applied at the outside of the pipe which is why, for the computation, we considered sectioning the different values of thickness mentioned above (1.5, 1.75, 2.0 and 2.25 inches).

The relative penetration of a copper LSC is considered to be to 0.9 times the width of the charge. This is based on a charge with a 75° angle liner. The next step is to establish the core load of explosive (C) for the charge of interest. Calculations were performed using these equations for the thickness mentioned in the last paragraph and the results are presented in Table 3.2.

Table 3.2 - Copper sheathed linear shaped charge data

Thickness to cut [in]	Charge width [in]	Core load of the charge [grain/ft]	Stand-off [in]	Charge weight for 36" pipe [RDX lbs]	Charge weight for 48" pipe [RDX lbs]
1.5	1.67	2865	1.17	3.86	5.14
1.75	1.94	3866	1.36	5.21	6.94
2.0	2.22	5073	1.55	6.83	9.11
2.25	2.50	6420	1.75	8.64	11.53

The core load for the optimal charges to cut 1.5 and 2.0 inch thick pipes obtained from simulations by DRDC Suffield and presented in Table 3.1 were respectively 3191 gr/foot and

[3] Cooper, P.W., Kurowski, S.R., *Introduction to the Technology of Explosives*, VCH Publishers Inc, New-York, NY, 1996.

5867 gr/foot for 1.5 and 2.0 inches thick material. The charge core values obtained from both methods are in the same range which confirmed the simulation work.

The charge length to cut a 36" diameter pipe as mentioned above would be 9.425 feet and 12.57 feet for a 48" diameter pipe. The total charge weights to cut pipes with the thickness of interest are presented in the last two columns of Table 3.2. Obviously, an important question was the availability of such a charge core load from the manufacturers as will be discussed below.

In order to compute the equivalent core load requirement in composition B, we used the ratio of Gurney energies ($\sqrt{2E}$) which is a good indication of the explosive ability to move metal and is currently used with shaped charges. The value for RDX is 2.93 km/s and 2.70 km/s for composition B. The density of the material must also be considered. In this case, the pressed RDX charges have a density of 1.65 g/cm^3 which is close to the value of 1.67 g/cm^3 typically obtained with cast composition B so they were considered equal. From this data, it was obtained that the total composition B charge to section the 36" pipe would weigh 9.4 lbs and 12.5 lbs would be required for the 48" pipe. Obviously, this would require a change in the charge design which was not be possible as described below.

3.4.3 Linear charge selection

Data on commercially available linear charges was reviewed with the charge data discussed above. Looking in the Accurate Energetics catalogue, (see Annex A), it was found that a copper lined LSC with a 4400 grain/foot core load of RDX would give a penetration of 2.25" in 1018 mild steel at a stand-off of 1.25 inch. This value is lower than the core value obtained from calculated value which is around 6000 gr/foot but no manufacturer had charges with core values close to that value. It was therefore decided to use the 4400 grain/foot core load which was deemed sufficient to cut the pipes which were most likely to encountered. Special rollers for the charge forming equipment were produced by Accurate Energetics to curve the charges to meet the different sizes of piles considered. The actual dimensions, presented in Figure 3.12 below, were requested from the charge manufacturer to finalize the selection of the casing system. The scaling of this charge is close to that of the Accurate charges.

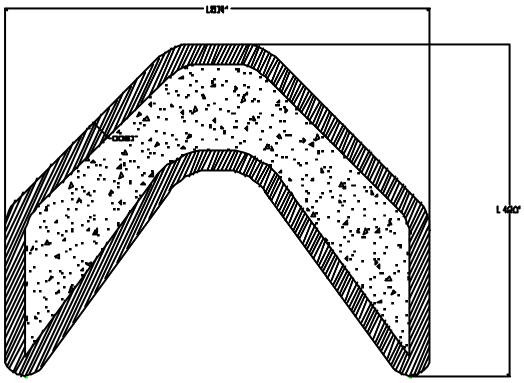


Figure 3.12 – Selected linear shaped charge dimensions

Simulations were performed with this charge and the 2D lagrangian model used is illustrated showing the jet formation after 0, 12, 20, and 30 microseconds in Figure 3.13.

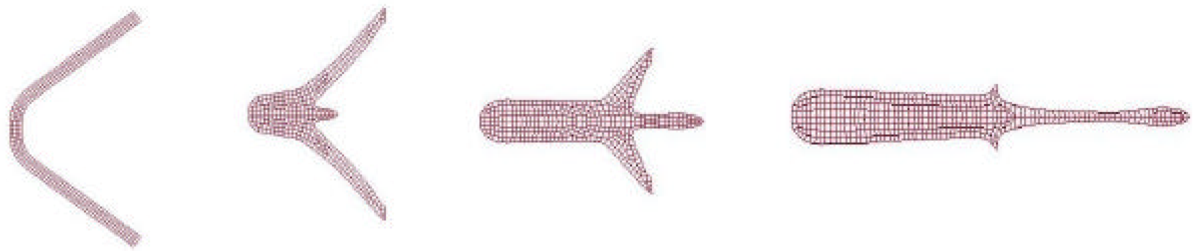


Figure 3.13 – RDX filled 4400-gr/foot linear shaped charge jet formation (not to scale)

From these results, a drawing of the required linear shaped charge subtending a 45° arc was prepared considering the available stand-off distance and the thickness of the casing material that will be described in Section 4.0 of this report. The pipe to be cut during the test at DRDC Suffield had 48" outside diameter and was 1.5 inch thick. When Accurate Energetics was contacted to order the required section of 4400 gr/foot linear shaped charge using the final design illustrated in Figure 3.14, we were told that they had done additional studies on the charges and that they had decided to replace the 4400 gr/foot charge by a 4000 gr/foot. They indicated that their tests showed similar penetration performance and that the charge was easier to manufacture. The charge dimensions were slightly modified to keep the same explosive charge density so the charge height was reduced from 1.42 to 1.375 inch and its width was reduced from 1.810 to 1.545. This height reduction enabled us to obtain a stand-off value closer to the optimal value.

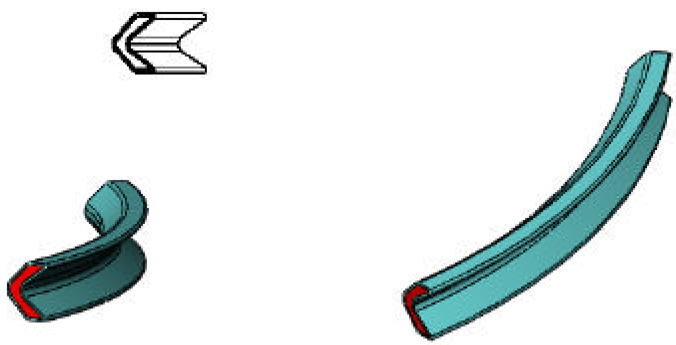


Figure 3.14 - Curved linear shaped charge design ordered for testing

3.5 Explosive filling

No readily available design for the composition B filled charge was available so it was decided to use the same charge design as for the RDX filled charge, in order to compare the cutting results with charges filled with both explosives during the tests at DRDC Suffield and then do the final choice of explosive after reviewing the results. An inert filling material, which could be pressed in the metal tubing to form a charge with dimensions similar to those of the RDX filled charges, but which could be easily removed was available from Accurate Energetics. Straight 12 inches and curved charges to fit the 48" pipe and subtending an angle of 45°, as discussed in Section 3.4, were ordered. Upon reception, the inert material was removed with high-pressure steam from inside the copper charge sheath. The charges were filled using a standard method used by SNC TEC to fill projectiles. Ancillary equipment to hold the charge straight up during the casting and cooling operation as well as a funnel adapter were developed. The filling set-up is shown in Figure 3.15.

Figure 3.15 – Composition B filling set-up

After filling, the charges were cooled in an SNC TEC proprietary system. The funnel and ancillary parts were then removed and the excess composition B at the filling end of the charge was cut with a band saw.

4.0 - ENGINEERED CHARGE DESIGN – CASING

While working on the linear shaped charge design, studies were also on for the development of the casing to hold the LSC and set it in the Scorpion™ system. This section describes the steps leading to choice of the casing used in the tests.

4.1 Requirements

Prior to the design, the requirements for the casing were reviewed and the following factors were retained:

- The casing had to be sturdy enough not to deform under the pressure generated by the water at the depth of the pile severing;
- The complete charge system with the casing had to be waterproof to ensure that no water could enter the shaped charge cavity which would reduce the performance;
- The casing had to be designed to ensure reliable initiation of the linear charges;
- The thickness of the casing was also important because the jet from the linear shaped charge can cut a given thickness of steel, as discussed above, therefore any additional thickness of material from the casing in front of the jet would reduce the thickness of pipe that could eventually be severed.

4.2 Considered design

When the first casing concept was drawn based on what had been used by ESI with the Scorpion™, the casing material was not established and the shape was only limited by the requirements mentioned in the last section. This concept is shown in Figure 4.1 below.

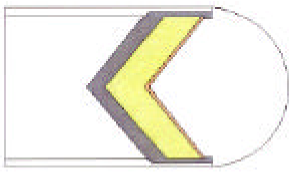


Figure 4.1 – Preliminary concept of casing

Three major casing designs were considered and will be presented in this section along with the advantages and disadvantages of each of them.

4.2.1 Flexible tube design

The simplest design considered is presented in Figure 4.2. This casing was planned to be made of rubber or a flexible tubing material. The flexibility of this liner design could enable adjustment of the charge and meet the pipe interior shape in cases where it is not completely round. Such a casing would present problems to seal the ends, principally when it deforms, so it would be very difficult, if not impossible to make such a casing waterproof. It would not be sturdy enough to set-up a system to ensure optimal stand-off distance resulting in a reduction of the performance of the linear shaped charge. An additional drawback was the size of tube required to obtain the required stand-off distance.

Figure 4.2 - Flexible tube design

4.2.2 Structural steel channel design

The second design considered was the use of a structural steel "C" channel design that would add some sturdiness to the design and could have the width of the charge, so the system was smaller. The two-dimensional simulation model for this design is illustrated in Figure 4.4. This design ensured that the stand-off remained at the optimal value. There is direct access to the charge for initiation and reduction of the casing width compared to the tube mentioned in the last section. The drawbacks are that it should be ensured that the ends and the area where the linear shaped charge fits on the channel are waterproof. The rolling of a channel with the stiffening legs towards the inside, as shown in Figure 4.3, implies that there is nothing to avoid their warping principally toward the ends. This warping would have then to be precisely corrected.

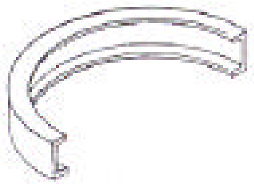


Figure 4.3 - Rolled C channel with stiffening legs towards the inside

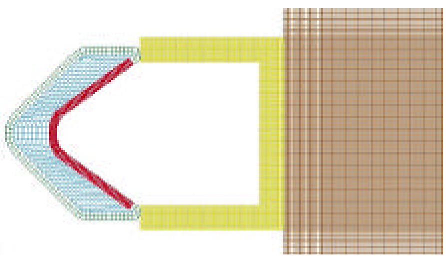


Figure 4.4 - Steel "C" channel casing design

4.2.3 Hollow Structural Section (HSS) design

The third casing design developed was based on the use of "Hollow Structural Section" or HSS for short. This type of structural section made of steel was considered a very good candidate for the following reasons. A casing design made of this material had the advantage of minimizing the surfaces to be waterproofed at the two ends. The sturdiness of the entire casing is inherent to this type of structural section which has straight rigid walls to allow precise positioning of the linear shape charge inside the casing. Although not available in all possible sizes, which could have been a drawback, a standard HSS was found with an internal width value close to the charge width and a height which could provide a stand-off close to the optimal value discussed above. The HSS wall thickness available as well as the chemical composition and mechanical properties of the steel are comparable to those of the structural steel channel used in the simulations performed with the channel system presented in the last section so all the results previously obtained indicating a minimal reduction of penetration remained valid. In terms of cost, this product being manufactured for the building construction industry it is easily available from most mill brokers.

HSS is available only as straight product, so the curving to required radius to fit inside determined pile diameter necessitates some specific manufacturing techniques. This point along with the indirect initiation of the charge through a wall was viewed as the major drawback.

The HSS based design is illustrated in Figure 4.5. The ends of the system are closed with plates screwed in place after placing the charge in the casing and setting-up the stand-off distance. Some water proofing material was used to obtain the required sealing.

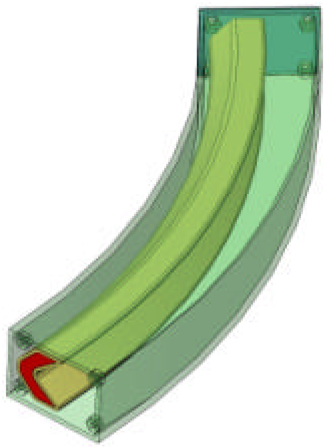


Figure 4.5 - Hollow structural section design

To validate the efficiency of HSS casing and confirm the design selection, some verification tests were performed. The resistance of the standard HSS wall to the pressure generated by a water column of typically some hundreds of feet had been questioned. A verification of the theoretical resistance of the HSS to this water column was done considering the wall of the casing submit to an uniformly applied pressure of water and verifying maximum stress apply to the wall and its deflection.

The stress value computed with these calculation is 73,760psi. Considering that the ultimate tensile stress is 85,000psi, the design is safe, although it is close to the yield stress of 50,000psi, considering that it is a very worst case analysis. The maximum deflection computed is 0.044". This value was considered negligible since as long as the casing remain watertight and enabled a proper initiation, there is no concern for the deflection. With a basic calculation model for the collapsing of a rectangular HSS, a first approach for verification of a theoretical collapsing pressure was also done. We obtained a collapsing pressure of 2551 psi, which corresponds to a water height of about 6000 feet; that is much higher than the required depth. The exact solution to the problem lies between the two cases presented here.

As mentioned above, the manufacturing of the casing, mainly the curving of the HSS to meet the pile to sever internal dimensions, was seen as a major concern. The casings are made of flat steel rolled, then formed as a hollow section and finally closed with a seam weld. Their fabrication process and material properties make them difficult to curve without large distortion. The simplest working method, which was eventually selected, was to use induction heating while curving. A curved section of HSS made to fit the interior of a 48" diameter pipe is shown in Figure 4.6. Wooden models of linear shape charges subtending a 45° arc were put on the curved HSS to show how the curves would match.

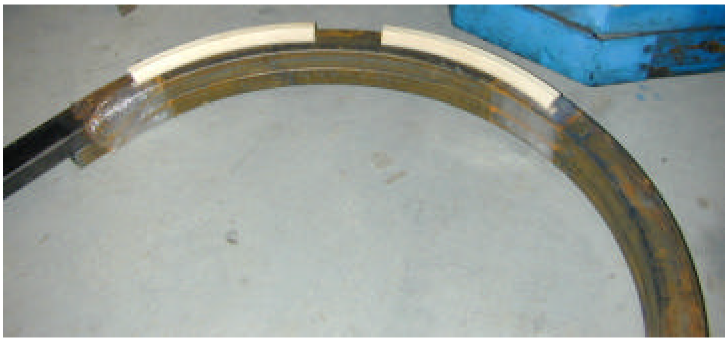


Figure 4.6 – Rolled HSS section to fit internal diameter of 48"ø pile

Following the success of rolling HSS to fit the internal diameter of a 48"ø pile, it was uncertain if HSS could be curved to fit smaller pipes internal diameter. The smallest diameter of pile to be severed was considered to be 24". A test to roll of the same type of HSS used for 48"ø to adapt it to a 24"ø pile was performed. The level of stress induced was high enough to produce wrinkles on the wall of the HSS where the initiation system would be sitting. Subsequently, a different thickness of HSS, 3/16" instead of 1/8", was considered and tested for bending to fit a 24" ø pile.

The straight HSS tubing was curved to the maximum arc leading to the required dimensions, which was found to be ~180° as shown in Figure 4.7. That figure shows two sections of HSS tubing bent to the maximum angle covering the full 360° for both 24" and 48 " diameter piles. After bending to that maximum angle, the casing section lengths subtended by 45° arc for a 48"ø pile were cut.

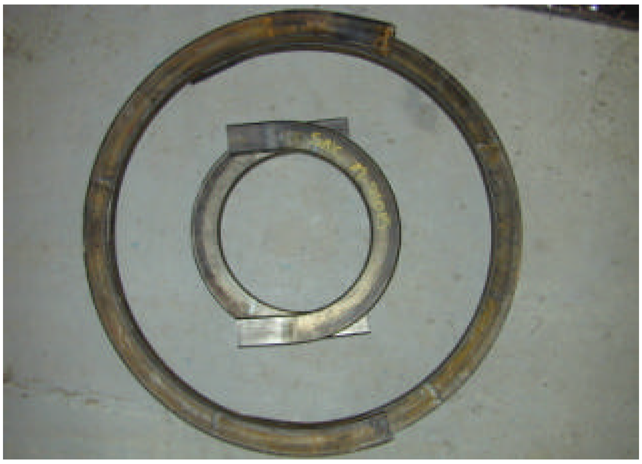


Figure 4.7 - HSS tubing bent to the maximum arc for 24"ø and 48" ø pile

The next issue to consider was the development of watertight closing of the extremities of the HSS casings. To achieve this goal, it was rapidly established that the surfaces to be assembled should match up as much as possible. The two open extremities of the casings were machined perpendicular to the section end to assure this match with the two machined cover plates. These parts are shown in Figure 4.8.

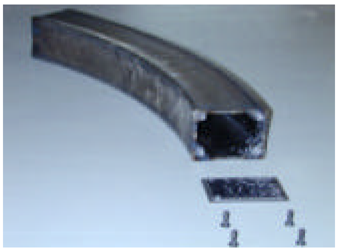


Figure 4.8 - HSS casing machined extremity, closing plate and fasteners

Although the fit obtained by the assembly of machined surfaces was viewed as the major consideration to make the casing watertight, the assembly items could be subjected to mounting and dismounting so the use of a gasket or a product acting as a gasket was considered to be necessary. A review of different products that could be used as a sealant for our use led to the choice of moldable sealants. Two sealing compounds, a 100% RTV silicone and an elastomeric rubber, were tested.

Although no definitive conclusions were reached with regard to one failed seal casing, the perfect results obtained for all the casings prepared with the elastomeric rubber led to the selection of this material for waterproofing.

At this point the casings were considered waterproof and sturdy. The main objective of the casing being to maintain the linear charge at a position where it will give the desired stand-off when initiated, the casing required some other improvements. These improvements to the casing related to the initiation system and holding system for the charge will be discussed in the sections describing initiation and charge holding presented later in this report.

4.3 Final selection of design

At this point the HSS casing design with the features described above was finally selected and they were manufactured for the preliminary testing at DRDC Suffield according to the drawing shown in Figure 4.9 for the curved sections.

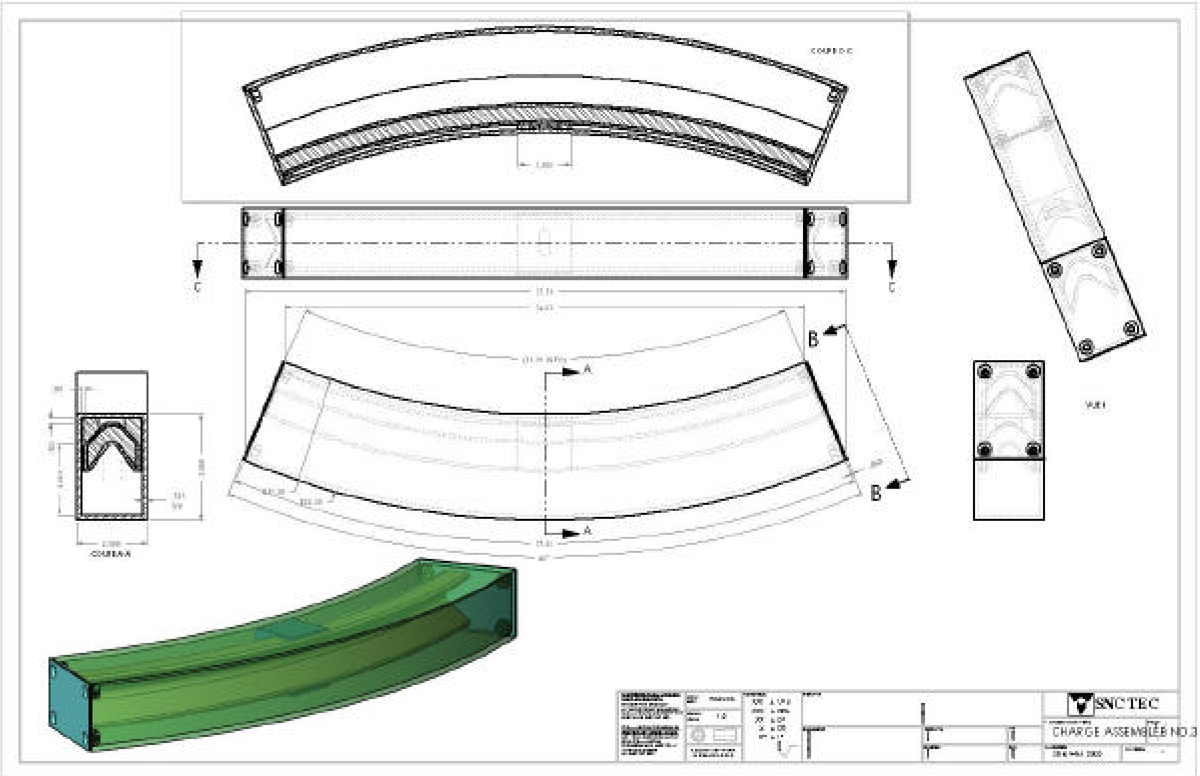


Figure 4.9 – Curved casing design for DRDC Suffield testing

5.0 - ENGINEERED CHARGE DESIGN – ANCILLARY PARTS

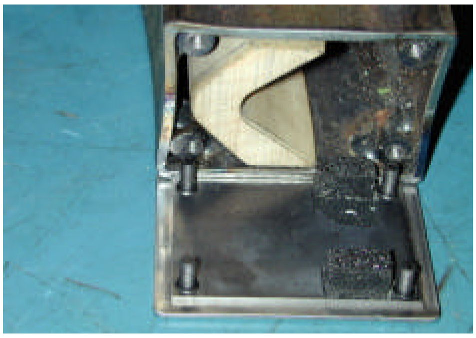
Along with the major parts of the charges presented above, other ancillary parts, such as the linear shaped charge standoff holding device and the initiation system, had to be studied considering their importance to obtain adequately functioning charges.

5.1 Linear shaped charge stand-off holding device

When the linear shaped charge and the casing design were selected, it became important to develop a method to obtain the required stand-off between the charge and the target. The requirements for such a device were reviewed and are listed below:

- The linear shape charge is completely enclosed in the casing therefore the stand-off holding device had also to be enclosed in the casing and installed in such a way to ensure that the charge would not move;
- This device had to ensure that a good contact was obtained between the booster holder and both the charge and the casing;
- The jet cutting ability of the shaped charge jet should not be affected, therefore the stand-off holding devices had to be positioned near the ends of the charges, possibly on the casing covers and be as small as possible.

A stand-off holding device design for each cover plate, composed of two small blocks which stood between the bottom of the charge and the billet nuts when the covers would be in place, was developed. This design is illustrated in Figure 5.1. Two types of materials, also shown in Figure 5.1, were considered: a rigid foam material called "Aerofoam" and a hard PVC (polyvinyl Chloride) type proprietary plastic named "Protane". Once the holders were positioned, they were set in place with glue.



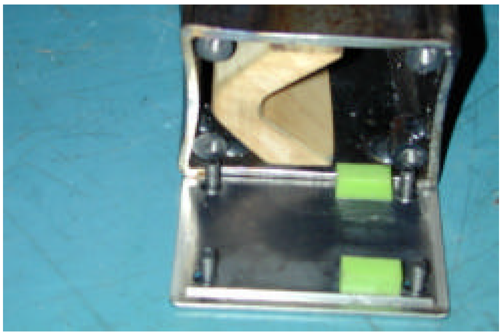


Figure 5.1 - Stand-off holding device – Aerofoam on the left and Protane on the right

A first series of test was performed to check the sturdiness of system and the ability to support both the charge and the booster holder when assembled inside the casings.

This testing was performed with a "jolt test" which is currently used to test the sturdiness of military systems. This test consists of a sequence of severe shocks produced by dropping, shaking and rolling over of the tested item. Even though the test itself was not totally conclusive, since no other charge holder system passed it without deformation and remaining completely intact, it was considered that the "Protane" block produced a better system since it did not deform.

As an improvement to get a more realistic testing, the "jolt test" was replaced with a drop test. Evaluating the forces imply to compress and release the Scorpion™ and the kinetic and potential energy implied, a drop height of 5 feet (1.5m) was consider to produce sufficiently rigorous test to check the retaining force of the holders.

To improve the holding forces three different commercial adhesive were evaluated, namely: Loctite 380 (Black Max), Loctite 409 (Super Bonder) and Loctite 454. Finally different surface preparation (sanding) and use of an ionic activator (Loctite 7471) were also tested.

With these improvements, once again, the results were only partially satisfactory because a small number of "Protane" block did not stay in place after the test.

The drop test was repeated another time but this time an elastomeric rubber was added between the covers and casing while the case was being closed. This elastomeric rubber is the same one used to ensure that the casing was waterproof. This additional material was found to add to the strength of the bond between the "Protane" blocks and the covers. An examination of the drop test results indicated that sufficient sturdiness was achieved for the LSC/casing assembly. The charge installation process is illustrated in Figure 5.2 and Figure 5.3.

Figure 5.2 - Set-up of "Protane" block charge holders with the elastomeric rubber

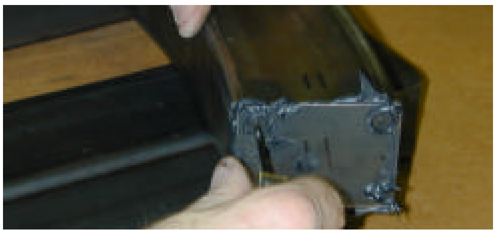


Figure 5.3 - Final Installation of cover plate on the casing prior to the drop test

5.2 Initiation system

Another important part of the charge system is the initiation. One important consideration was to avoid putting holes in the casing that would then require to be plugged to ensure that the system remained waterproof after putting the initiation system in place. In addition, the results of the charge testing had shown a reduction of penetration directly under the initiation point so different concepts were modeled and tested. The use of a closed HSS was concluded to be the best casing concept, as indicated in Section 4.0, but some preliminary work was carried out to develop a reliable initiation system during the casing development phase and the results had to be eventually adapted to the final casing design. The next sections will describe the computational and experimental work done to develop this system.

5.2.1 Computer modeling

The development of a 3D model was first attempted with similar adaptive meshing techniques to those used with the 2D models. Numerical mesh instabilities associated with the method of calculation within the code and limitations with the meshing technique employed would not allow the model to predict jet behavior. The 3D model was eventually developed with euler based elements to eliminate these difficulties. The drawback of the euler based elements is the requirement for a much finer mesh and longer computer run times. The simulations with the 3D model showed the same initial penetration geometry noted in the experimental results. Approximately 2-3 charge diameters are required for the penetration to run-up to full penetration. It was considered that this could be addressed by increasing the head height of explosive at and about the detonation point to achieve the required penetration. The 3D model was also run to quantify the change in penetration of the charge due to the curvature as illustrated in Figure 5.4. The numerical simulations indicates a negligible reduction in performance results from the curvature of the charge for a 48-inch pile.

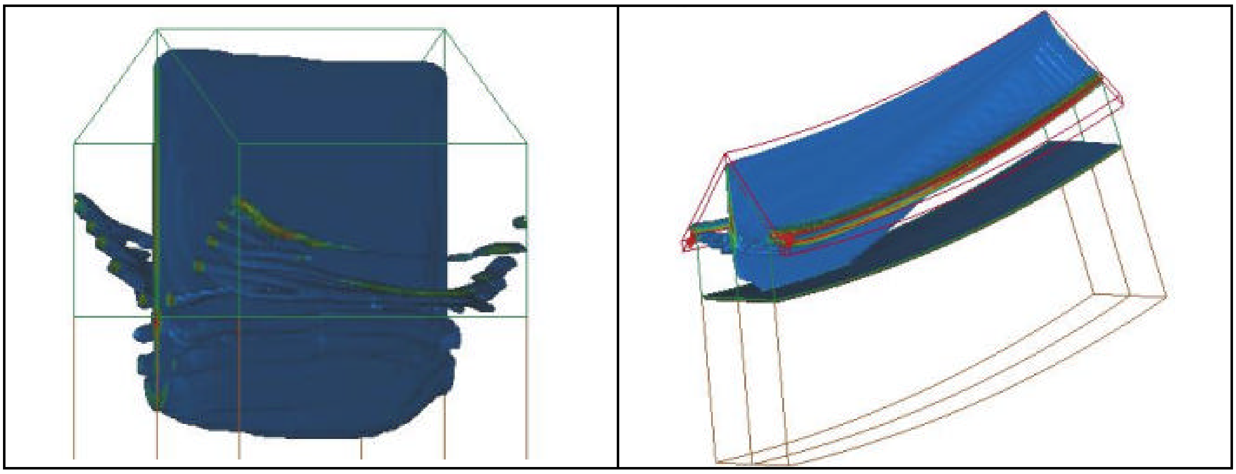


Figure 5.4 - Initiation test modeling

Numerical modeling of the initiation event indicated that an improvement could be obtained near the initiation point by using multiple initiation points (three initiation points).

5.2.2 Testing

An experimental trial was conducted with three initiation points tested by the numerical modeling. This initiation concept reduced the size of uncut portion of steel. The plate was severed by the action of colliding shock waves and the blast loading. The testing arrangement and sectioning results on a steel plate are illustrated in Figure 5.5 and Figure 5.6 respectively.

Figure 5.5 - Three points initiation arrangement

Figure 5.6 - Three point initiation sectioning results

In an effort to reduce the remaining portion of limited penetration, a six-point initiation system based on two of the above units spaced at one charge width was tested. The length of the uncut portion did not change, remaining at approximately two charge widths, but the height was reduced to approximately 3/8" as shown in Figure 5.7.

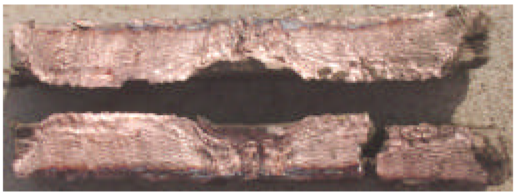


Figure 5.7 - Six point initiation system sectioning results

A similar initiation can be achieved using a single detonation point for the initiation system. The initiation system will then propagate the detonation wave to the six detonation points on the charge itself.

During DRDC-S testing, it was preferred to use a simpler system and, if the performance would have been not acceptable due to insufficient cutting ability below the initiation point, these concepts would then have been revisited.

Concurrent to the development work done at DRDC Suffield on the initiation system, some development was also done at SNC TEC. The objective of this development at SNC TEC was to insure that the developed initiation system would be compatible with the developed casing and enclosed linear shape charge, as presented above.

The initiation concept needed to have an initiator outside of the watertight casing creating a shock wave going through the casing thickness to initiate a booster that in turn would detonate to initiate the linear shape charge enclosed inside the casing. The initiator considered was a standard non-electric initiator typically used by ESI for this type of work. The simpler concept of booster holder developed was made of a wooden shaped device fitting over the linear shape charge with a hole on top to contain the booster explosive. C4 explosive was considered as the booster explosive. The use of wood to fabricate the holder had the advantage of being readily available and easy to machine while being antistatic when the charge is slid inside the casing. This concept of the booster holder is shown in Figure 5.8.

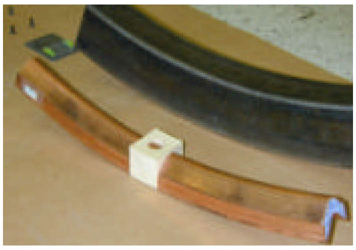


Figure 5.8 - Complete charge design part including booster holder system

In order to position the initiator where it is required on the surface of the charge assembly and obtain efficient initiation of the booster explosive inside the casing, different arrangements were considered. The final arrangement selected was a linear groove machined on the surface with the dimensions selected to fit with the non-electric initiator. The end of the groove corresponding to the initiator end was placed on the center of the charge design as seen in Figure 5.9.

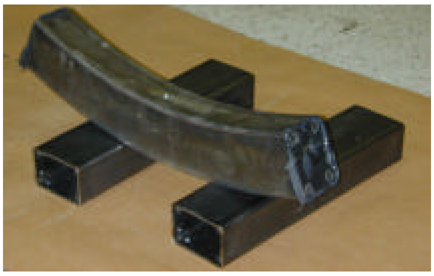


Figure 5.9 - Linear groove to install the initiator

In conclusion, the initiation concept evolved from the work done at DRDC Suffield showing the potential of the Linear Shape Charge initiated from a central booster and the possible improvements with multi initiation points.

The precision required for the multipoint booster holder would cause difficulty, not only in the manufacture and assembly of the charge, but would also impact on the robustness of the charge.

The design would eventually have to be use efficiently in non-ideal conditions as those that would be met in the Gulf of Mexico.

6.0 - EXPERIMENTAL TESTING AT DRDC SUFFIELD

Following the completion of the charge design including the linear shaped charges, the casing and the initiation system, the parts were manufactured as planned in Task 3 of the project. Those were then tested at DRDC Suffield to verify the functioning of the charge and prepare improvements in view of the final testing at ESI. In this section, we will first start with a quick description of the material ordered and manufactured for the testing, then the testing procedure will be described and finally the results will be presented.

6.1 Charge manufacturing

Two types of charges were manufactured. Straight or flat charges were used to compare pressed RDX filled charges with DRDC Suffield composition C4 filled charges, evaluate the effect of the casing on penetration and to study the initiation set-up. Curved ones were to be tested against the actual 48" diameter pipe design and perform explosive comparison between pressed RDX and composition B. The length of the individual curved sections was adjusted to the maximum allowing a good quality casting which was subtended by an arc of 45°, as discussed in Section 3.5. In order to get adequate comparison between both explosives tested, all the curved sections were the same length.

6.1.1 Linear shaped charges

As indicated before, the 4400 grains commercial linear shaped charge manufactured by Accurate Energetics was originally selected but, as mentioned above, results indicating that a 4000 grains linear shape charge was providing very similar sectioning performance while being easier to manufacture led us to order this charge. This charge design was therefore selected for the tests. A quantity of 24 curved sections were ordered (~16.5" long subtended by an arc of 45°) filled with the standard pressed RDX filling. Another 12 sections were ordered with the same characteristics, but filled with an inert filling. The inert filling was removed upon reception at SNC TEC and replaced with the Composition B explosive, as discussed in Section 3.5. The drawing of the charges is presented in Figure 6.1 for composition B filled charge. In addition to these curved sections, 12 straight or flat sections of 12" long were ordered with the standard pressed RDX filling.

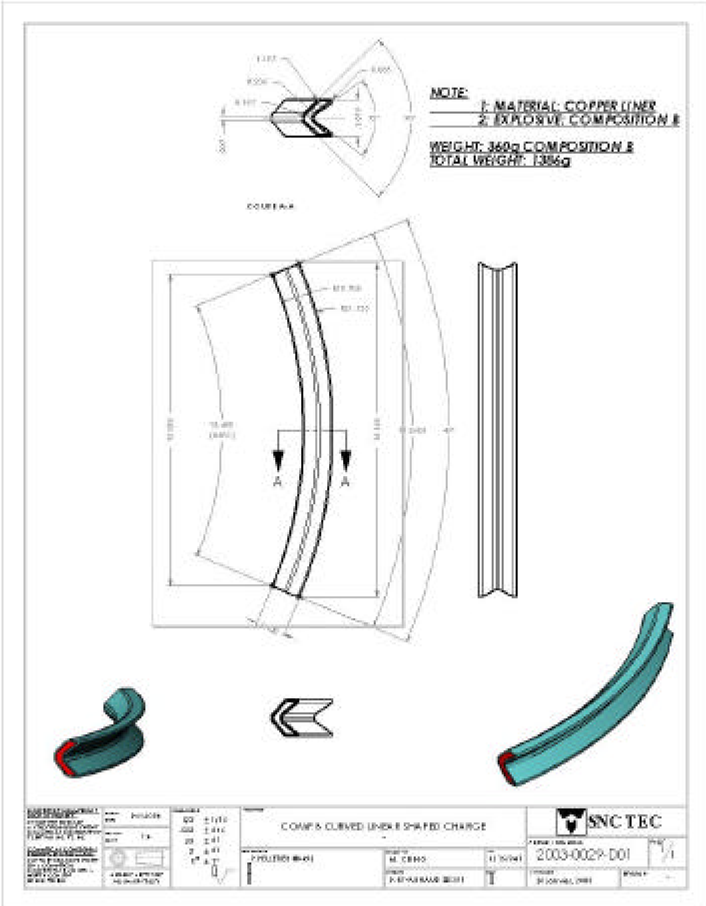


Figure 6.1 - 45° arc composition B filled linear shaped charge for severing 48" ø pile

6.1.2 Casings

The hollow structural section selected during the design step, as described in Section 4.0, was HSS 2" x 3" x 1/8" thick tubes. This material was ordered and manufactured according to the following specifications. For the straight charge tests, straight casings dimensioned to enclose the straight 12" linear shape charge were fabricated. One such casing is pictured in Figure 6.2.

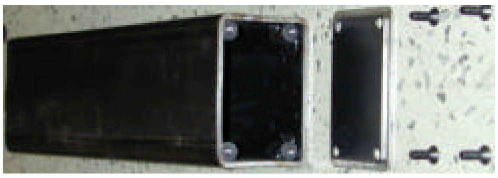


Figure 6.2 - Straight charge casing with milled end extremity and cover plate

Once the casing manufacturing was completed, the location of the initiator was determined and the required groove was machined on the top outer surface of the casing.

For the curved charge tests, the HSS tubes had to be first curved by induction heating as discussed in Section 4.2.3. The curved tubes were then sectioned to the exact length to enclose a linear shape charge subtending a 45°arc to section a 48"ø pile. Once the HSS was curved, the other steps to prepare the ends and machining of initiation location groove were the same as for the straight casings. The final casing charge arrangement including both the linear shaped charge and the casing are shown in Figure 6.3.

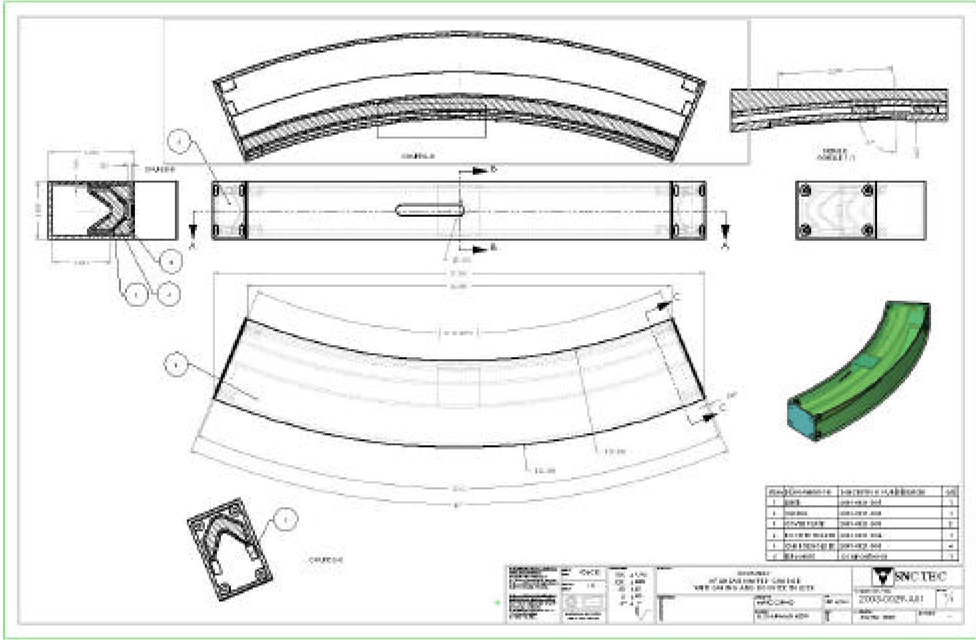


Figure 6.3 - Curved casing for sectioning 48" ø pipe

A sufficient quantity of casings for the number of charges described in Section 6.1.1 was manufactured and sent for the testing planned at DRDC Suffield and described in Section 6.2.

6.1.3 Ancillary parts

As discussed in Section 5.0, in order to help produce a watertight casing, it was decided to perform the initiation through the casing hence the groove on the outside surface described in the previous section to ensure perfect positioning. Inside the casing, a wooden booster holder was used to contain pressed C4 explosive in a hole. Two designs of booster holder with different holes sizes were manufactured and sent to Suffield in sufficient quantity for the tests.

6.2 Field testing

The testing at DRDC Suffield was planned with all the parties involved (MMS, DRDC Suffield, ESI and SNC TEC). One purpose of the tests performed at DRDC Suffield was the measurement of the performance of the selected LSC filled with both pressed RDX and composition B in order to finalize the explosive choice and decide if the selected LSC was performing as expected. Another important goal was to test the effect of the casing in the performance reduction. The major parts of the testing planned at Suffield took place as expected from March 3rd to 6th, 2003. One test was postponed until the following week because of the very cold weather.

The original test plan included the following tests:

- Initiation tests with straight LSCs filled with RDX to compare their performance to previous initiation tests performed by DRDC Suffield with C4 charges;

- Initiation tests with casings using straight LSC filled with RDX to evaluate the effect of a casing on performance;

- One test with three curved LSCs filled with RDX enclosed in casings to evaluate the performance against a pile section;

- One test with three curved LSCs filled with Composition B in casings to evaluate the performance against a pile section.

Different arrangements were tested for the explosive acceptor inside the casing or booster explosive. Were tested packing with composition C4, Detaprime® and Detasheet® .

The nonel initiator used alone on the outside of the casing was found to not initiate reliably the booster charge through the casing wall. To improve the initiator efficiency, tests were performed using Detaprime® and Detasheet®.

The first set of tests was performed on both straight and curved pressed RDX filled LSC. These tests were performed with the bare LSC charge, both without casing and in casing. The straight RDX filled LSC without casing showed a reduced penetration below the initiation system, which had been observed previously when testing was done during the development of the optimal design LSC testing by DRDC Suffield.

The enclosing of the straight pressed RDX filled LSC in a casing showed the same kind of behavior.

The last series of test was performed with curved Composition B filled LSC inside casings. The test with only one charge against a target showed performance similar to the linear charge filled with pressed RDX. The test performed with three charges mounted in an arrangement similar to what will be obtained when using the Scorpion™ showed less performance than the charges filled with pressed RDX. This led to the choice of RDX filled LSC as the preferred design for the remainder of the project.

The "Protane" blocks used to support the charge were found to be difficult to work with during the tests, so simpler alternatives were considered. A charge holder made of two wooden blocks spacers at the extremities was selected when it was found to be sturdy enough and have a minimum effect on jet formation and penetration during tests.

6.3 Conclusions

The general conclusions from the testing performed at DRDC-Suffield as part of Task 4 of this project were the following:

- Shaped charge penetration is not significantly changed if either saturated sand with water or water are used as backing behind the target;
- Penetration of the target is reduced below the initiation point;
- A Detasheet® based initiation system proved to be the most successful. The importance of ensuring very good contact of the different parts of the explosive train (initiation system and LSC) was evident from testing. This is even more important since the initiation system is outside the casing while the booster is inside the casing;
- Dual initiation increases the penetration in a localized area where the detonation waves interact. This increase comes at the expense of reduced overall penetration as the charge runs-up from two points with reduced penetration below them as indicated above;
- The pressed RDX linear shaped charges outperformed the Composition B filled charges in perforating the pile wall, resulting in additional blast related damage so pressed RDX charge was selected as the LSC main charge explosive for the remainder of this program;
- Preliminary tests using wooden blocks as charge holders did not indicate a reduction of performances compared to the "Protane" blocks design so it was decided to use this type of holders in future work based on the fact that this concept is easier to use.

At the end of the tests, discussions took place regarding the booster charge; mainly how to produce it easily and reliably. Different concepts were considered and it was decided that additional work should be done on this subject prior to the final tests.

7.0 - CHARGE DESIGN MODIFICATION AND TESTING

In this section we will present the work done on the considered modifications and testing following the preliminary tests at DRDC Suffield. This work was performed as part of Task 5 in the contract work plan. In addition, prior to the testing in the Gulf of Mexico, it was decided to test both the charges and the blast measurement system in a quarry lake. This work was part of Task 7a.

7.1 Linear shaped charge and casing design

The charge dimensions were originally designed to section 48" diameter piles. To cover a complete circumference eight sections of 45º, two for each of the four Scorpion™ legs, were used. When the pressed RDX LSC charge filling was chosen over the Composition B filled charge, as mentioned in the conclusions presented in Section 6.0, the restriction to use 45º arc section became irrelevant. Even if a clear advantage from overlapping the charges was not identified during the DRDC Suffield tests, it was decided to use such charge arrangement based on the previous ESI field experience. Using these premises, it was decided to use charges sections subtended by a 95º arc for each Scorpion™ leg. This choice simplifies the manipulations by reducing the total number of linear shaped charge/casing assemblies to be mounted on the Scorpion™ from eight to four and facilitates the mounting on each Scorpion™ leg. It also produces an overlap of approximately 1.5" at the extremities of adjacent charges.

Some discussions implicating MMS, ESI and SNC TEC reached to the conclusion that 48"ø piles would be the preferable target because this size of pile would bring results which will encompass all diameters and thickness smaller than that size. Unfortunately the availability of this type of pile in the Gulf was low and, in the opinion of ESI and MMS, it was very improbable that enough piles of 48"ø would be available at the time the final testing in the Gulf was planned. Based on this information, it was decided to design and manufacture charges for a second diameter which was considered more likely to be available. Based on data available to MMS and ESI, it was decided that 30"ø piles with 1" thick wall were the most likely to be available for the demolition work to be conducted during the period of interest. The test plan was therefore modified in a way to severe one of these two diameters (30"ø or 48"ø) depending on their availability. The thickness was considered only to compute the length of charge corresponding to fit the inside of the pipe because the form of linear shaped charge was not changed.

As mentioned above, segments to cover an arc of 95° were to be used to achieve overlapping for the 48"ø piles. Using the same idea of overlapping, the 90° arc was extended to 98° for the 30"ø piles in order to keep the same overlapping length (1.5"). The linear shaped charge designs are illustrated in Figure 7.1 for the 48" pile and in Figure 7.2 for the 30" pile. Important data on both charges is presented in Table 7.1.

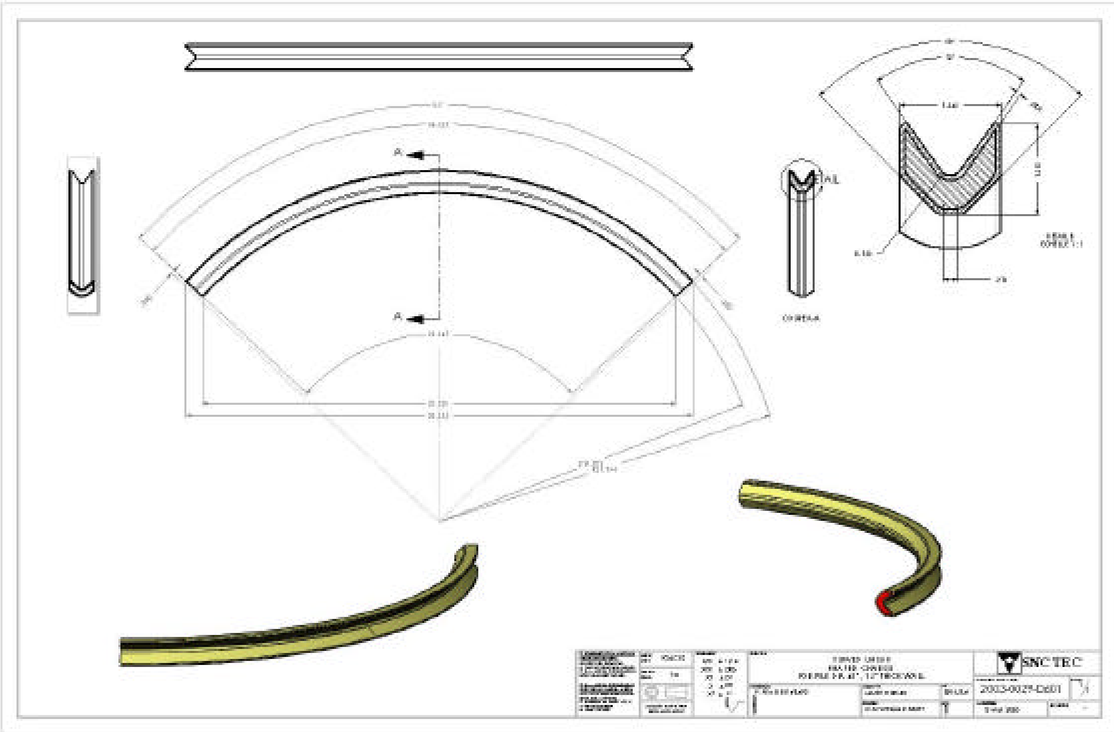


Figure 7.1 - Linear shaped charge design for severing 48" ø pile

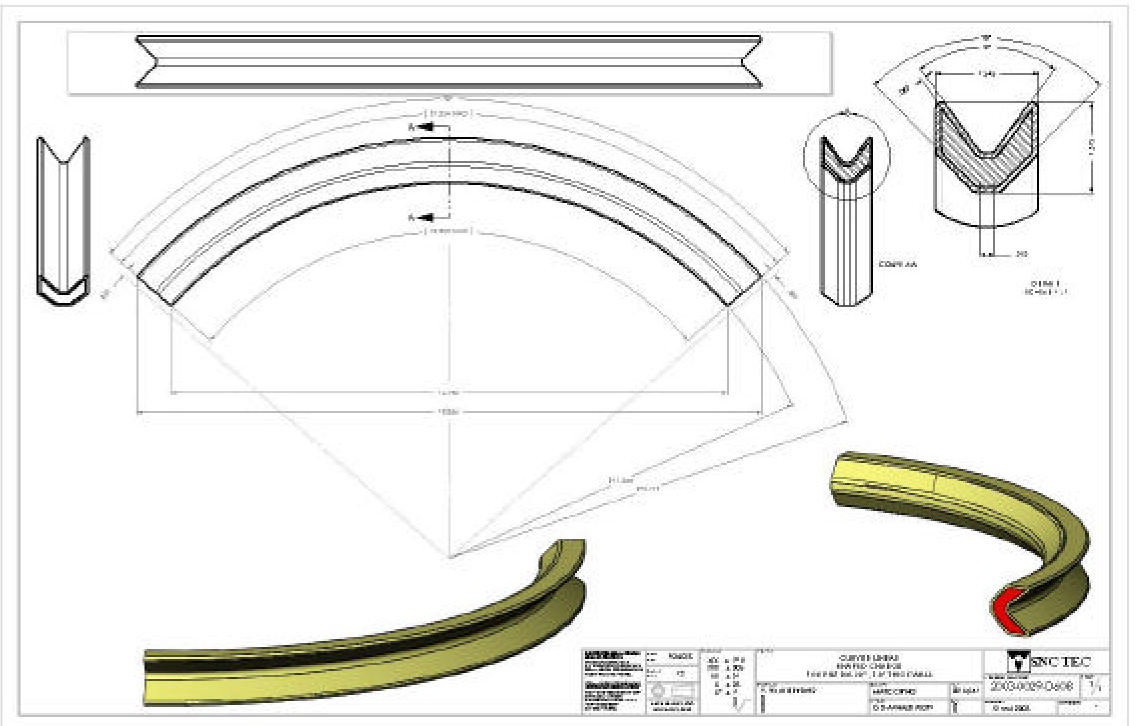


Figure 7.2 - Linear shaped charge design for severing 30" ø pile

Table 7.1 - Dimensions of curved linear shape charges

Pile to be severed	Arc angle degree	Subtended arc length (external) inch	Subtended arc length (internal) inch	Outer radius	Inner radius	Individual charge weight lbs	Total charge weight lbs
48"ø, 1.5" thick wall	95°	34.52"	32.24"	21.15"	19.78"	1.64	6.58
30"ø, 1.0" thick wall	98°	21.25"	18.90"	12.21"	11.34"	1.01	4.05

The casing design dimensions also had to be adapted to contain the two different LSC required to section 48"ø and 30"ø piles. They are illustrated in Figure 7.3 and Figure 7.4 respectively. For information, the distance between the top of the LSC and the inside surface of the HSS is equal to 0.125" in both cases.

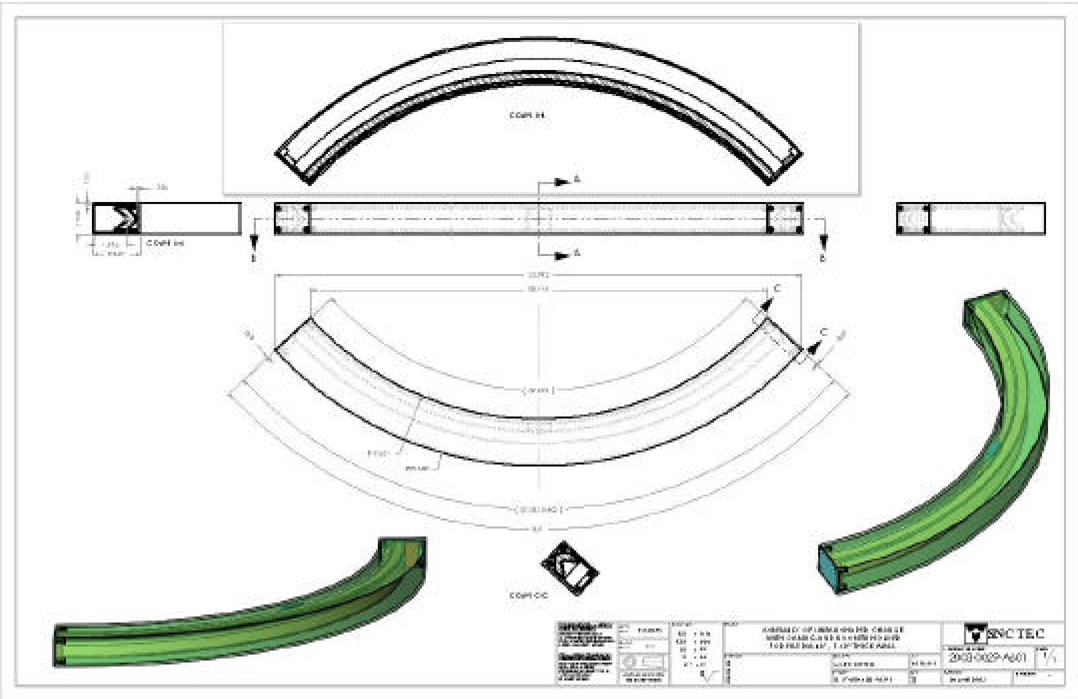


Figure 7.3 - Casing for explosive charges to sever 48" ø pile

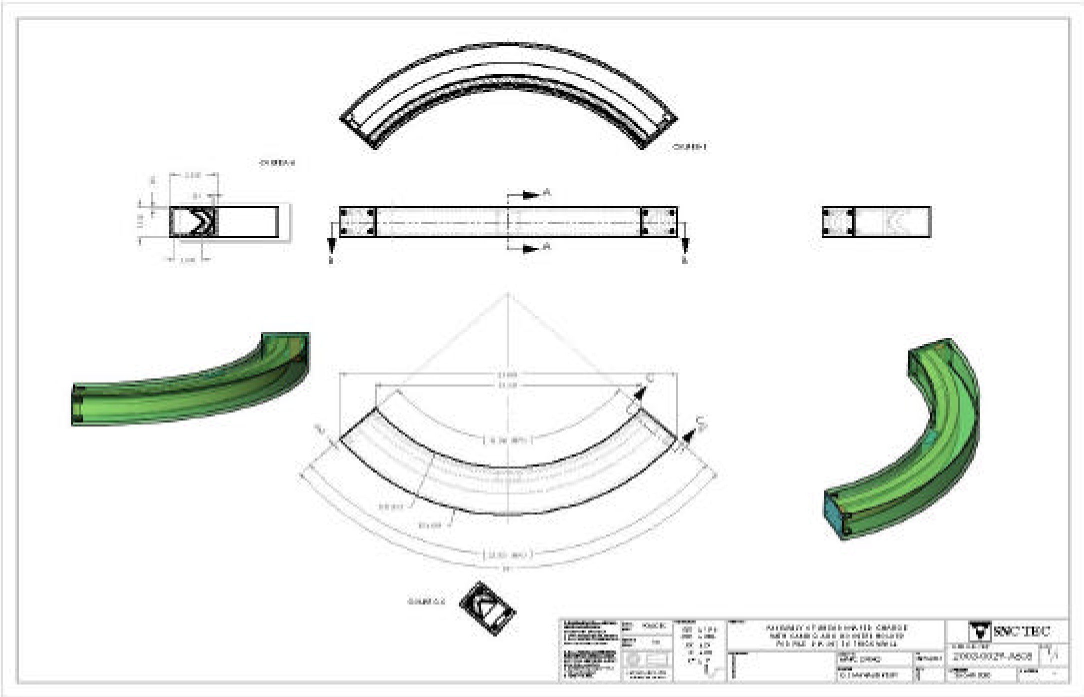


Figure 7.4 - Casing for explosive charges to sever 30"ø pile

7.2 Manufacturing of new HSS casings for ESI and Gulf of Mexico testing

The HSS material for the casings was ordered based on the designs dimensions for 48"ø and 30"ø piles. The bending of the HSS to 95° arc sections for the 48"ø piles was performed without problems using the same method used to produce the previous 45° sections. When the HSS sections were curved to 98° arc sections for the 30"ø piles, they showed the same wrinkles on the inside diameter as those already seen on HSS curved to the 24"ø pile, as discussed in Section 4.2.3. After considering and testing 3/16" wall HSS instead of 1/8" wall, the 1/8" wall with wrinkles was sent for ESI testing to evaluate the real influence of the wrinkles. This could include air gap and degradation of the shock wave through the casing to the LSC, (see Figure 7.5 to Figure 7.7).

The quantities of casings to be manufactured for each diameter were also discussed. It was agreed that 30"ø piles had more chances to be available than 48"ø piles for the Gulf testing. The casings were therefore ordered for a minimum of six 30"ø piles and two 48"ø piles, enabling us to test in the Gulf and at ESI on both diameters.

Along with design improvements on casing dimensions to improve the sectioning ability of the system by charge overlapping, the quantity and locations of initiation points on the charge casing was further discussed. Based on DRDC Suffield testing, it was considered that dual initiation would bring the advantage of increased penetration in a localized area where the detonation waves interact but reduced overall penetration due to the penetration reduction below the initiation points as discussed before. In addition to this consideration, the dual initiation brings a redundancy effect that is considered as a security element in use of explosives by the blasters. This last consideration lead us to the decision to use dual initiation. These two initiation points were located at 2¾" on each side of center of the casing.

Figure 7.5 - Mounting of the worst wrinkled casing prior to testing

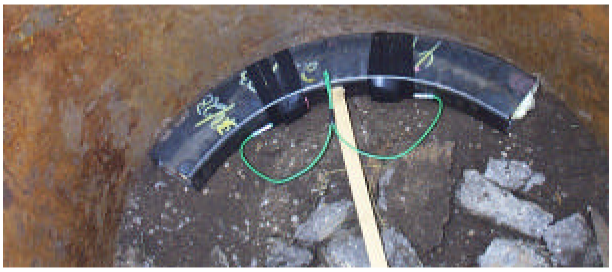


Figure 7.6 - Testing arrangement for the wrinkled casing in a 30" ø pile

Figure 7.7 - Resulting cut from the wrinkled casing in a 30" ø pile

7.3 Initiation system and booster holder device

At the end of testing at DRDC Suffield, it was mentioned that it would be good to have a system that would reduce explosive handling and the resulting effort. Some design effort was therefore put on a system to prepare and hold the booster explosive charge in place. Such a booster holder device concept and its considered arrangement on the charge is shown in Figure 7.8.

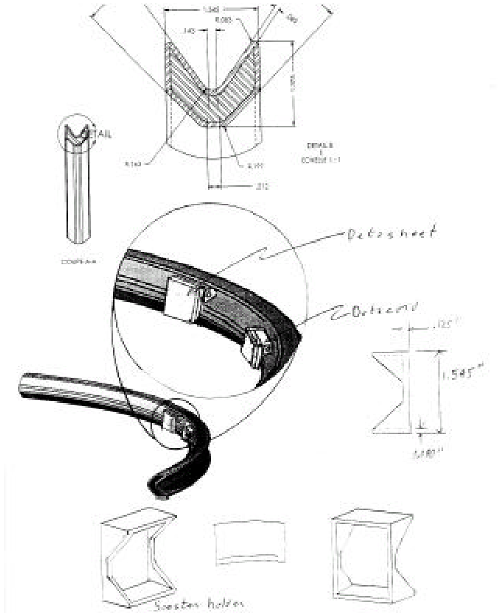


Figure 7.8 - Booster explosive mould concept and installation overview

In a preliminary concept of the booster holder, it was desired to have a reusable mould to prepare the booster charge but it quickly appeared advantageous to develop a booster holder concept that would become part of the booster resembling those originally designed before the DRDC Suffield testing. Another aspect considered in elaboration of a booster holder was safety. The possibility of building up and discharging static electricity during inserting of the charge should therefore be considered. With all these aspects in mind, the design of the booster holder was developed to be easily manufactured out of different materials and easily adaptable to the charges for sectioning both 48"ø piles and 30"ø piles. The booster holder is illustrated in Figure 7.9 for 48"ø piles, the same concept was developed for 30"ø piles.

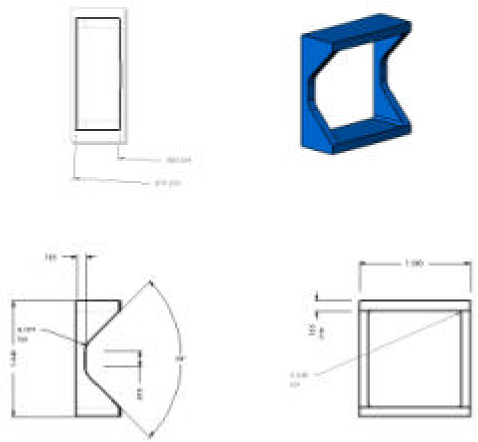


Figure 7.9 - Booster holder 48"ø pile

Once the design was developed, the question of the material to manufacture them was studied. Three different materials were considered in the study: polycarbonate, laminated paper and aluminum. Samples of the design were fabricated with each of these materials. They were then compared to each other based on ease of manufacture, elasticity (in order to hold booster explosive), fragility, sturdiness, etc. The review of all those considerations led to the choice of aluminum as the best-adapted material for our use. Easily available as extruded tubing, it is machined to make the final required piece. The materials were also tested for their tendency to charge with static electricity. Aluminum still appeared as the best choice based on static electricity charge. It was then concluded that booster holders made of aluminum presented the best properties in term of sufficient rigidity to receive and hold booster explosive and had sufficient sturdiness to be handled inside of the casings.

Although different explosives for the booster had been tested at DRDC Suffield led to the choice of Detasheet®, some additional tests were performed at the ESI test range. These tests were performed by ESI using RDX and PETN sheet explosives. This testing showed good performance of both explosives to initiate the linear shape charge but better cutting performance under the point of initiation was obtained with Detasheet®. This confirmed our choice for the final tests in the Gulf.

7.4 Linear shaped charge holder

As mentioned in Section 6.3 on the DRDC Suffield testing, it was concluded that wooden blocks had minimal effect on the charge jet performance. The same concept was retained for the preliminary testing at the ESI test range. Many sizes of wooden blocks were fabricated to fit all variations of casings dimensions. A typical arrangement is shown in Figure 7.10

Figure 7.10 - Wooden block charge holder

7.5 Blast measurement – Testing definition

Since the beginning of the project, the possibility of measuring the effect of underwater use of explosive was considered an option to be exercised if the testing at DRDC Suffield provided good results. The results obtained and described in Section 6.0 led to the award of the option. It was defined in the original plan that measurements to be taken were to include peak pressure, impulse and energy flux density. An original pattern of measurement gages was defined with several vertical arrays of tourmaline piezoelectric gages providing sensors at different heights and distances from the explosive source. This arrangement, which is shown in Figure 7.11, was defined assuming 100 feet of water and the charges inside the piles 15 feet below mud line.

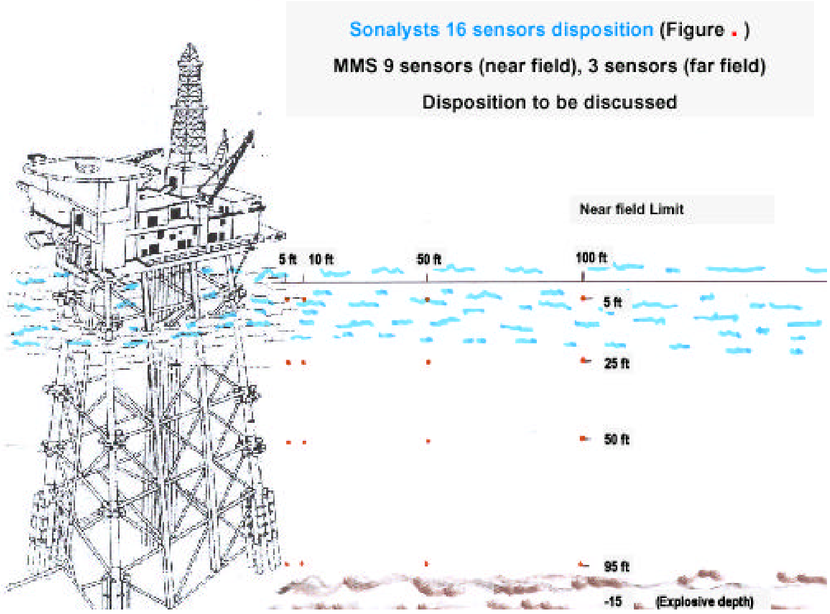


Figure 7.11 - Array of sensors disposition assuming 100 feet of water depth

Minimum standards guidance for collection of data defined by MMS included requirement for site characterization measurements data such as: water depth and temperature, salinity profile, sound speed profile, sediment type and structure type description. As for the explosive charge to be tested, the net explosive charge weight and explosive charge type were to be recorded. The requirement document also included data on the collection plan such as the need of nine pressure transducers at near field (within 100 feet of the explosive source), three far field at varying distances and depths. It was requested that the locations of pressures transducers and the depth of the burial of explosive were to be precisely measured.

The data to be obtained from the test were peak pressure, impulse and energy flux. The peak pressure or peak overpressure is the maximum value of the pressure wave resulting from expansion/compression of the media as recorded at given distances from the source of blast. For the array sensor deployed the blast pressure rises to a maximum in terms of microseconds (μsec) and after it declines. The impulse is the integral of the pressure over time. The energy flux density is a measure of change of energy across a unit surface perpendicular to the shock wave propagation. The possibility of determining relationships and trends in the data collected was also discussed as possible future work. This analysis would include dampening effect of sediment and structures, water depth and properties, sediment type and properties, and the effect of explosive mass on shock wave propagation and acoustic properties from the explosive detonation.

Regarding the relationships and trends to be computed, it was established that it was not part of the original contract. It would be left to MMS to determine if, from the quantity of experiment and data gathered, it could be possible to establish such relationship and trends. With only one or two experiments, the establishment of some relationship and trends was definitely not a certainty.

As discussed earlier it was also established that a dry run for the measurement equipment would be an asset before carrying out the final measurements testing in the Gulf of Mexico. Task 7 was broken in two sub-tasks. This dry run was established as Task 7A and named "Preliminary tests at ESI" while the second sub-tasks or Task 7B was "Testing in the Gulf of Mexico". A meeting to review the tests results was planned between the two parts of the task.

7.5.1 ESI test range

As indicated above, some design confirmation tests prior to testing on actual platforms were planned at the ESI test range as Task 7A. The details of these tests have been documented in Annex D of the Background Documents[4] to this report. The major points will be reported in this section.

When testing at the ESI test range was planned, two diameter piles (30" and 48") were considered based on the fact that it was not clear at that time what size of oil platform piles would be available for sectioning in the Gulf. As part of this testing series, some individual tests were planned on individual charges to prove functionality and sectioning performance of the linear shape charge mounted with both stand-off and booster holders. It was the occasion to confirm that the casing design was fully watertight and that initiation through the wall of the casing was efficient. Testing at ESI test range was also used to verify complete arrangement of charges when deployed with the Scorpion™ on both pile diameters targeted. Finally, these tests were used to check the Sonalysts equipment.

The highlights of results obtained during the tests are presented in the remainder of this section. One sectioning test was performed in a 30"ø pile using one linear shape charge mounted in a casing with wooden block stand-off holder with one booster made of PETN and one made of RDX.

Figure 7.12 - Cut produced with a LSC in a 30"ø pile

[4] Saint-Arnaud, D., Pelletier, P., Poe, W., Fowler, J., *Oil Platform Removal Using Engineered Explosive Charges: In Situ Comparison of Engineered and Bulk Explosive Charges – Final Report Background Documents,* April 2004.

A similar test was conducted with the same arrangement, but in a 48"ø pile with RDX and PETN boosters (see Figure 7.13).

Figure 7.13 - Cut produced with a LSC in a 48"ø pile

The cut under the RDX booster presented clearly the appearance of the jet passage, while under the PETN booster a part of the cut was not clearly associated with the jet passage but looked more like crack propagation. This confirmed the selection of RDX as the booster.

Underwater testing using Scorpion™ system with the developed engineered charges against piles were conducted in a quarry lake near the ESI location. One test was performed against a 30"ø pile using four complete charges mounted in the Scorpion™ with wooden blocks stand-off holder for the linear shape and two booster charges of RDX inside each casing. The pile was set at the bottom of the quarry lake at about 15 feet depth. Each linear shape charge-casing assembly was made to be watertight using the gasket sealant previously tested and chosen for the project. The charges initiation was produced by nonel initiators placed between two layers of Detasheet®. There was two initiation points per charge for a total of eight for the total system with the charges ready to be deployed in the 30"ø pile.

Once the complete Scorpion™ system was lowered at the required level, the charges were deployed. The charges deployed in a 30"ø pile are illustrated in Figure 7.14.

Figure 7.14 - Scorpion™ with charges deployed in a 30"ø pile

When these operations were done, the Sonalysts measurement equipment was set-up. The array of sensors was at 30 and 55 feet from the explosive source while acquisition system and analyzer were on the ground at a safe distance Figure 7.15.

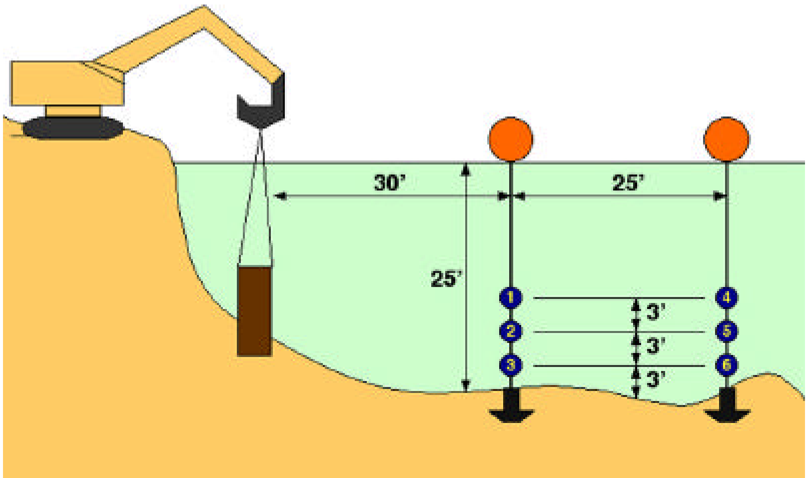


Figure 7.15 - Deployment of sensors array

To be precise, the sensors array was first set-up for a 30"ø pile, but then, for technical reasons described in the Annex D of the Background Documents[4] to this report, the first sectioning was performed on 48"ø pile, 1.5-inch thick which was then followed by the 30"ø, 1.0-inch thick pile severing. When everything was in place, the charges were initiated. All the charges were correctly initiated and the jets produced complete cut through the pile wall. Figure 7.16 shows two views of the cut, the left picture shows a face on view of the cut and the right picture shows a side view with the offset resulting from the configuration of the Scorpion™.

Figure 7.16 - Face and side views of the cut on the 30"ø pile

The two views of the cut show clearly the severing on the entire circumference. There is no large deformation or mushroom effect and no remaining tabs between the cuts done by the four legs of the Scorpion™ .

The blast transducers in the array picked up the pressure wave from the blast produced by the charges. The signal transmitted to the equipment was recorded and then further analyzed. The complete analysis done including graphs of transducer shock pulse data can be reviewed in Sonalysts report, presented in Annex E of the Background Documents[4] to this report. In their analysis, Sonalysts scientists indicated that they could distinctly identify the blast from the shaped charges. Being in a highly enclosed area, part of the many observed peaks were attributed to reflection in the pipe structure or charge delays and bottom or quarry wall reflection. On the first set up which was on a 48"ø pile, the transducers 1 & 2, (see Figure 7.15), did not worked properly, this was repaired and they all recorded the pressure data for the 30"ø pile.

The other test was performed on a 48"ø pile. The same arrangement as for the 30"ø pile was used with the exception of the engineered charge dimensions which were made to fit this size of pile, as described earlier in this section. Deployment of the charges with the Scorpion™ was done in the pile before immersion in the quarry lake (see for reference Figure 7.14) showing a 30"ø pile.

Difficulty was encountered in positioning the pile on the irregular floor of the quarry lake. Several attempts were made before the pile was successfully position albeit in a slightly canted position. The repeated manipulation of the pile with the charge and Scorpion™ system inside may have resulted in damage due to shaking and jolting of the experimental set up.

When these operations were performed, the measurement equipment was redeployed. The arrangement of the array of sensors was similar to the one used for 30"ø pile and placed at 30 and 55 feet from the explosive source while acquisition system and analyzer were set-up, see for reference Figure 7.15.

When everything was in position, the four charges were detonated. The final result obtained was a partial severing of the pile. The resulting cuts are shown in Figure 7.17 with a numbering of the four junction points of Scorpion™ legs. We can observe a tab between two cuts as well as the fact that although the cuts overlapped each other, some one of them were deviated.

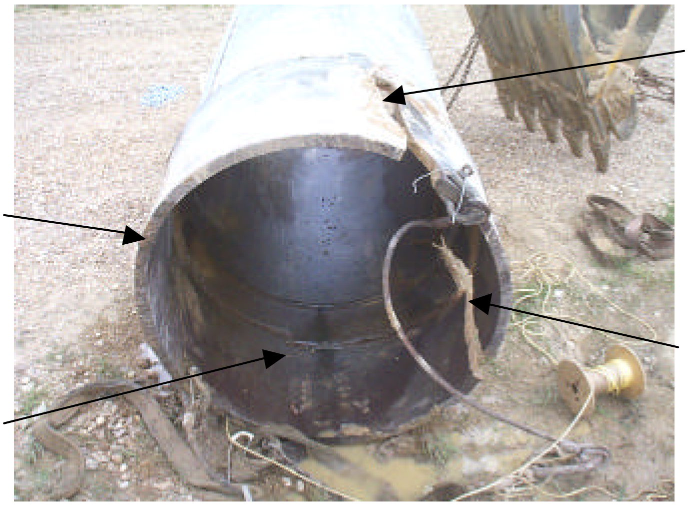


Figure 7.17.-.Global view of 48"ø pile after severing

The partial severing at the four junctions of the Scorpion™ legs and between them, were closely examined, see Figure 7.17 & Figure 7.18.

Even if the severing was incomplete, it appeared that the four charges were initiated. As in the case of the 30"ø pile, the resolution of the equipment used by Sonalysts specialists enabled them to identify the blast from all four shaped charges. As already mentioned, unfortunately the sensors 1 & 2 from the array see Figure 7.15, did not work during this experiment. The situation was readily corrected by Sonalysts specialists, and it did not reappear in the next experiment.

A post mortem analysis of all the events was conducted to try to explain why the charges did not perform optimally to completely severe the pile.

The experimental preparation was investigated and no anomalies on loading or assembling procedures were uncovered. Charges and casings were handled to ensure positioning, sealing and maintain of all the assembly.

The charge installation procedures was also questioned.. With the severe shaking imposed on the casings inside the pile while the pile was set-up in the bottom of the lake, it appeared realistic that the stand-off holding blocks in one or two casings may have shifted and could be the most likely explanation for the results. If that happened, it would have caused one or many of the following events. The initiation would have been done from only one point instead of two. The initiation could have resulted on one or two points but without intimate contact between the inside of the casing and the booster material. The intended initiators could have produced no initiation, the initiation resulting from the shock wave of the adjacent charges at one or both extremities. These events would combine with a lost of the correct stand-off distance and a possible slant of the LSC inside the casing. A close look to some details of the cuts at the junctions of severing give some support to this last hypothesis. The left picture on Figure 7.18 show the same cut in continuity with the right picture. Looking at the shape of the extremity of these two cuts it can be seen that both turn upward see Figure 7.18. The two picture from Figure 7.18 show the same cut going from junction #4 to #1.

Figure 7.18 - View of the two parts going from the Junction # 4 to # 1

With these two pictures side by side, the slanting of the LSC inside of the casing appeared very probable. The slanted charge being initiated near the center, the jet produced followed the orientation of the LSC which is more apparent at the extremities.

While the explanation of the imperfect set-up of the charge appeared very likely, it was difficult to confirm it without a doubt. So, it was decided to perform some additional tests on 48"ø pile cutting before the Gulf testing. It was also decided to improve the holder system sturdiness by the same occasion. One solution to make it sturdier was to put a longer and therefore more stable wooden block holder in front of the linear shape charge. While this changed nothing in terms of stand-off distance, this meant interference of wood on the jet formation and reduced penetration on a longer distance. Expanding foam was also considered as a possible material to be used to produce stand-off holder because it would have a minimum effect on the jet because of its lower density, see Figure 7.5 and Figure 7.6, with the longer wooden block on the right and the expanded foam on the left.

This test was conducted on a 30"ø pile. This test was also used to verify the effect of wrinkles on the casing made of 1/8" thick steel. As mentioned earlier, the wrinkles were presumed not to cause any loss of initiation efficiency or to influence the charge performance. If the wrinkles had an influence, it was expected we would observe either no initiation or a weakened cut under initiation point, when compared to previous tests on 30"ø pile using a casing with no wrinkles.

The results showed that even if the cut was complete under the charge it was observed to be weaker locally under the charge holder made of the long wooden block (see Figure 7.7 and Figure 7.19).

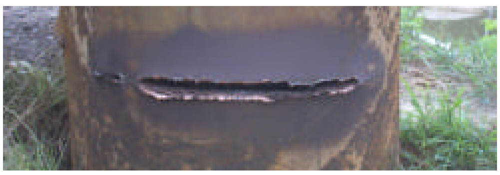


Figure 7.19 – View from outside of the resulting cut from the wrinkled casing in a 30" ø pile

The previous assumption that wood density was sufficiently low to permit an efficient formation and moving of the jet was therefore proven incorrect. From the analysis of the results of this test and previous ones, it appears that if the wood blocks were too thin so they were not solid enough to hold the linear shape charge and booster in intimate contact with the HSS top surface. If this happens a tilting of the LSC may result inside the casing and in the best case a deformed jet is produced, or, in the worst case, it may result in an air gap and no initiation by the initiator system. If, on the other hand, the wooden block was too thick, it could have an influence on the optimal jet formation and therefore reduce its efficiency.

In the case of the expanded foam, although it had a very minimal effect on the jet, it was difficult to set in position and, more importantly, it did not provide the required rigidity to the system.

This last test completed the ESI test range testing series as originally planned and the following conclusions were made:

- Efficient and reliable initiation of a linear shape charge and severing of 30"ø piles could be obtained using either 3/16" or 1/8" thick wall casings even if there are wrinkles formed on the surface of the latter one;
- The reliability of the charge initiation and ensuing severing of 48"ø pile still required some improvement. The most likely modification area being to work was considered to be the wooden standoff holding blocks;
- Data acquisition and measurement for peak pressure, impulse and energy flux were performed in accordance with expectations. Sonalysts specialists viewed the problem with two sensors not working in one deployed array during one test as a non-recurrent problem and they considered that this should not happen during the Gulf final testing. There was therefore no remaining question about measurement technique and this part of the deployment was considered ready for the final testing.

It was also recommended to conduct additional tests on the charges to section the 48"ø piles to obtain initiation and severing as reliable as those obtained in the 30"ø piles. Two series of tests were planned in sequence. A first series implied development of stand-off holding blocks. The goal of that first series was to validate different materials and configuration to be used as stand-off holding pieces and it was planned to perform it using straight charges. The purpose of the second series of test was to use the results of the first series to select the optimal stand-off holder and apply it to curved charges used to section 48"ø piles.

The recommended tests were eventually conducted. For the first series of tests, two designs of stand-off/charge holder were considered: a modified PVC pipe section and a shaped wood block. Both designs were developed and some prototypes were manufactured. The wooden holder is illustrated in Figure 7.20. They were subsequently tested by ESI looking at sturdiness of the assembly, ease of handling and resulting sectioning obtained with the charge. It was concluded by ESI that the two concepts were working equally well during the tests involving their explosive technicians.

Figure 7.20 - Shaped wooden charge holder design

The second series of tests was then conducted to complete Task 7a. These tests were done on improved 48" charge design including the two different stand-off holding devices described above. These tests took place at the ESI facility on August 4th, 2003. The tests were witnessed by people from the New Orleans MMS office. A complete circumferential cut (360°) was achieved, as desired. Both stand-off holding devices showed similar good results. Finally a slight advantage on the ease of handling led to the choice of the wooden holder.

With the successful completion of this testing of the improved 48" charge design, two designs of array with proven efficiency for the two pipe sizes of interest (30" and 48") were therefore considered available for the final testing in the Gulf of Mexico on actual platforms planned for Task 7b. Both have been tested and found working well underwater in what was considered similar condition as offshore.

8.0 - FINAL CHARGE DESIGN

Following the last series of tests performed, the charge design including all the ancillary parts that insured the functionality of the complete system was finalized. The charge parts can be quickly described as follows:

- The RDX filled linear shape charge curved to the correct radius to sever the pile of interest. The curvature radii for two different pile diameter, 30"ø and 48"ø piles, have been developed.
- The hollow structural section (HSS) casing curved to the correct curvature to meet the inner circumference of the pile to be sectioned. HSS thickness of 1/8" were proven to be acceptable for both pile diameter to section. As in the case of the linear shaped charge, curvature radii for both 30"ø pile and 48"ø were developed. Outside of the casing, two sections are machined directly over the location of the enclosed boosters explosive holder to ensure optimal positioning of the initiator systems. Cover plates, milled to fit without gap and ensure the assembled charge is watertight, are used to close the ends of the casing. In addition, a gasket sealant is applied on the cover plates to ensure that the final casing arrangement is completely watertight. The cover plates are assembled to the casing with four threaded billets welded on the inside corners of the casing. The cover plates are tied to the casing by four taper screws inserted in the cover plates.
- The charge holders insure that the linear charges do not move in the casing. They keep the charges in contact with the complete initiation system including the booster and maintain the shaped charge stand-off distance. The selected holder was the shaped wooden block. Two holders situated at both extremities of each charge were used.
- The booster holder allows confinement of the booster and keep intimate contact with the linear shape charge and the casing wall. The holders are made of aluminum and two types, one for each pile diameter considered (30" and 48"), were designed to ensure perfect fit. There are two boosters on each charge that are placed each side of the centerline to ensure a beneficial security redundancy.

The drawings of these different parts designed for the charges to sever the 30"ø and 48"ø piles are presented in Annex F of the Background Documents[4] to this report.

9.0 - FINAL TESTING

The final experimental task of the contract was to test the charge design mounted in the Scorpion™ system against actual platform piles in the Gulf of Mexico and to compare the blast obtained with these engineered charges against 50 pounds bulk charges C4. In this section, we will first present some details of the test plan and then discuss the targets which have been sectioned using the charges designed for a 30"ø pile. Unfortunately, no target containing 48"ø piles was available during the testing time frame, although the charges to sever such pipe dimensions were manufactured. In consequence this part of the testing was cancelled. This will be followed by the presentation of the details of the results and finally their analysis.

9.1 Test plan

The tests were carried out in the Gulf of Mexico according to the test plan presented in Annex G of the Background Documents[4] to this report. The tests described in the plan aimed at two objectives. The first one was to confirm that the engineered charges developed and mounted in the Scorpion™ system could entirely severe 30"ø piles on actual platforms in the Gulf of Mexico. The second objective was to take blast measurement on both the engineered charge and bulk charge as well as data on the test environment as requested by MMS for future use.

In the original test plan, the chosen structures were assumed to include four targets each. These four targets were supposed to be three piles and one well. The original plan was to sever two piles with the Scorpion™ system while the remaining pile and the well were to be severed using bulk charges.

Ideally the three legs and the well have to be severed quasi simultaneously. If not, the structure would become unstable with so few supports. Therefore all the severing should be done within seconds.

The requirements for the structures to be severed were that they had to be similar and, as indicated above, they had to be made of three piles of 30"ø and one well. The diameter of the well could be different than the piles diameter. Each structure had to allow the use of the Scorpion™ on two piles with the possibility of using bulk charges on one pile and on the well.

The acceptance criterion was the complete cutting of the piles.

As previously mentioned, measurements to be performed during the test were such as to enable the measurement and recording of blast pressure data. The peak overpressure was obtained from the curve and the impulse and energy flux values computed. Typically the impulse value is obtained by the integration of the area under the curve of the pressure versus time graph. The energy flux value is obtained by computing the area under the curve of the square of the blast pressure versus time graph. After each test, targets were to be photographed to evaluate damages. Any remaining partial structures cut were also to be photographed for evaluation of depth and shape of penetration.

Other measurements on the environment were to be performed concurrently. Sonalysts personnel was to provide a CTD (Conductivity, Temperature and Depth) logger to get measurements of water depth, temperature and conductivity. Information on sediment type and structure was to be provided by MMS. Details on explosive charges were to be provided by SNC TEC and ESI.

9.2 Targets description

Two structures were identified for our testing to prove the efficiency of the severing system. These structures in the Gulf of Mexico were located at block 21 in South Timbalier. They belonged to Huber Energy and were named J.M. Huber # 97 and J.M. Huber # 120. Those structures were at approximately 5 to 7 miles from the shore and 7 to 9 miles from dock facilities in Port Fourchon. The map presented in Figure 9.1 shows the general area where block 21 is located as well as some idea of the water depth in the area.

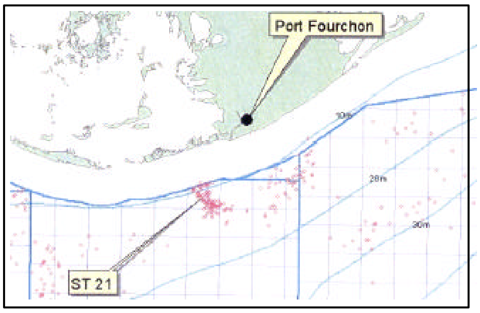


Figure 9.1 - Block 21 structure location in South Timbalier

The review of the information available on the two structures suggested that actual dimensions and conditions of the structures were possibly different than the descriptions in the available drawing at MMS. A "pre-mobilization inspection" of the identified structures was therefore suggested and accomplished on October 7th, 2003 by a team including MMS and ESI personnel. This inspection enabled to confirm that both structures had three 30"ø piles and that one structure did not have a well. This inspection also clearly confirmed that underwater visibility in this area was too low to permit efficient localization of the sensor array by divers team, which led to the rent and use of a sidescan sonar by the MMS people to perform this operation.

Following this "pre-mobilization inspection", the emphasis was put on the schedule for the testing mobilization. As the two identified platforms were available, it was a question of timing for the team involved (MMS, ESI, Sonalysts and SNC TEC) and the availability of the barge. A big barge is essential to decommission this kind of structures to insure complete removal of all dismantled parts and to perform the related operations such as cleaning.

The first testing mobilization took place between November 10^{th} and 14^{th}, 2003. A second inspection was performed on November 14^{th}, 2003 on both structures to get confirmation on some construction details such as legs angles and spacing between members. The purpose of these measurements was to obtain the exact location of the sensor array with respect to the actual position of the piles and sources of blasts. Pictures taken during this inspection are shown below. Figure 9.2 shows structure #97. The three 30" piles can be observed but there is no indication of the well. Structural damages and active corrosion can be observed on the structure. Figure 9.3 shows structure #120 also from block #21. The three 30" piles can be observed with the off-centered well. This structure, as the previous one, shows structural damage and active corrosion. The right side of Figure 9.3 shows structures #120 on an angle where it can be seen that the entire structure is twisted.

Figure 9.2 - Structure #97

Figure 9.3 - Structure #120

Unfortunately no structure was decommissioned on this first testing mobilization, for reasons out of control, the barge which was planned to be available for this effort happened to be offsite during this period. Then a new window of opportunity for the decommissioning was discussed and planned to be between November 20th and 23rd, 2003. For this new period the team who perform the test was made of MMS, ESI and Sonalysts personnel. The decommissioning of the two structures was effectively completed during this period.

9.3 Experimental set-up

The actual testing took place between November 20th and 23rd, 2003. As indicated in the previous section, the structures were not exactly as expected in the test plan. While structure #120 had three piles and one well, structure #97 had only three piles and no well was found, either visible or submerged. The level of corrosion and structural damages made it difficult to lower the Scorpion™ systems in place (inside the pile, 15 feet under mudline), which consequently led to some modification. Only one pile was severed with a Scorpion™ assembly on each structure because of this problem. On structure #120 this meant that two piles and the well were severed with bulk charges, while two piles from structure #97 were severed with the bulk charge. The quasi-simultaneous severing of the piles and the well however remained a valuable method to obtain charge comparison data.

The decommissioning operations began with platform #97. The first operation was to remove the upper section of the platform. This first operation was done by cutting the topside without the use of the explosives and then loading it on the barge, see Figure 9.4. The mud was extracted from the inside of the piles at least up to the position expected for the explosive charge.

Figure 9.4 - Structure # 97 as topped

After the inside of the piles was cleaned, the Scorpion™ and the bulk charges were lowered in the piles at about 15 feet under mudline. Once at the required position, the Scorpion™ was deployed. Before explosive initiation final set-up, the sensor array was deployed, see buoy alignment on Figure 9.4 and its position confirmed with two sonar, one operated by MMS and another one on the Derrick barge, (see Figure 9.5).

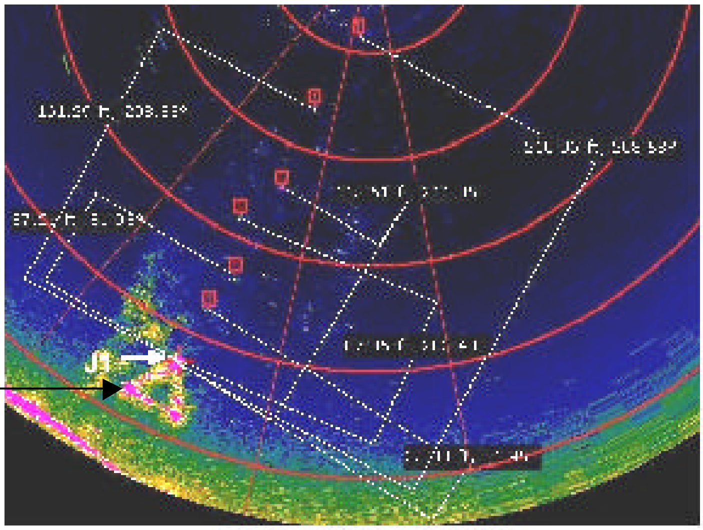


Figure 9.5 - MMS Sidescan sonar readings

The positions of the reflectors indicating the localization of each tourmaline sensors gauge was determined according to the pile closest to the deployment of the sensor array. The details of the sidescan sonar localization readings are shown in Annex H of the Background Documents[4] to this report.

Two measurement of water depth, temperature and marine conductivity were conducted with the RBR XR-420 CTD logger prior to the two experiments. The first series of measurements was taken the day before the first experiment (Structure #97 decommissioning) and the second series on the day of the second test (Structure #120 decommissioning). The second series of data was more difficult to measure due to the rough sea state, but good data was obtained so this method is very reliable. The data recorded data is presented in Table 9.1 while details can be found in Annex I of the Background Documents[4] to this report.

Table 9.1 - Data obtained from the CTD readings

Date	Data for Structure	Time	Conductivity (mS/cm)	Temperature (°C)	Pressure (deciBars)	Depth (m)	Speed of Sound (m/sec)
11/21/03	# 97	8:55:03	42.79	23.17	25.37	15.11	1523.39
11/23/03	# 120	14:44:40	43.29	23.03	21.59	11.36	1523.48

Along with the decommissioning operations of the structures, sediment sampling was to be done by MMS. The objective was to provide a more complete characterization of the soil environment where the blast had to travel. McClelland Engineers, Inc. and Fugro Inter, Inc. had previously done exhaustive geotechnical investigation in the surrounding of the structures for

Tenneco Oil and Exploration and Production in 1982[5] and 1984[6]. It was considered more valuable for this project to use these studies instead of performing analysis of two new soil samplings for the two structures. The soil samplings performed in those previous investigations showed that soil consisted from soft to stiff olive gray clay. They had been taken from two sites respectively located at about 1.2 and 3.5 miles away from structure #97. Data on these sampling are presented in Annex J of the Background Documents[4] to this report.

9.4 Experimental results and analysis

9.4.1 Pile severing procedure and results

A calibration test charge was fired to verify the functioning of the sensor array prior to the first experiment (severing of Structure #97). The results showed that three sensors from the twelve deployed array did not function (sensors E, J & K). It was unfortunately not possible to correct the problem because of the short time available to perform the decommissioning.

A 50 pounds bulk charge was lowered in the pile closer to the sensor array while, the Scorpion™ system with the engineered charge and a second bulk charge were localized in the piles further away (see Figure 9.5). When all the set-up was completed for Structure #97 removal (first experiment), the initiation system was connected and the explosive charges on the three piles were detonated. The results indicated that the pile with the Scorpion™ was only partly severed. To completely sever this pile, a bulk charge was lowered at a position deeper than the previous Scorpion™ location. These operations were necessary in order to inspect the structure and to see the results of the first attempted severing done with the Scorpion™. This last operation was successful and the structure was finally removed (see Figure 9.6).

Pile # 3 partly severed with Scorpion™

Figure 9.6 - Removal of structure # 97 after final severing.

[5] McClelland Engineers, Inc, *Geotechnical Investigation, Boring 1 , Block 27, South Timbalier Area, Gulf of Mexico*, Report to Tenneco Oil Exploration and Production, October 1982.

[6] Fugro Inter, Inc., *Soil and Foundation Investigation Well no.11, Block 22, South Timbalier Area, Gulf of Mexico*, Report to Tenneco Oil Exploration and Production, February 1984.

The second structure to be decommissioned was #120. One pile was sectioned with the Scorpion™ assembly while the two others and the well were severed with 50 pounds bulk charges. The same set-up procedure was used for the charges as for structure #97, except that the exact positioning of the sensors in the area could not be determined due to boat propeller wash "overshadowing the sidescan sonar".

A calibration test charge was also fired before the severing of structure #120. This verification of the sensor array showed that only one of the twelve deployed sensors did not function this time but, as the previous day, it was not possible to repair it during the time frame available.

Then, the testing took place. Although some work had been done to avoid the problem of the Scorpion™ deployment experienced in the previous test, it appears that it was not totally resolved because the same problem is believed to have occurred in this second test since the pile containing the Scorpion™ delivered charge was not completely severed and about one third of the circumference showing signs of cut was observed as in structure # 97. To complete the severing, a bulk charge was then installed in the pile partly severed with the Scorpion™.

9.4.2 Pile severing results analysis

Based on previous tests done with the Scorpion systems and the review of the final cut after recovery, it appeared that the most likely explanation for the incomplete severing of the pile by the engineered charges mounted on the Scorpion™ system was an incorrect deployment of the system. The collapsed or partly collapsed Scorpion™ would have been lying on one side of the pile, where the charges would have been in good contact with the wall. This typically corresponds to a contact surface of about 1/4 to 1/3 of the circumference of the pile. This imperfect deployment of the Scorpion™ system would have resulted in a partly severed pile with about one third of the circumference being cut. This appears to be consistent with what was reported by ESI representative. Another possible explanation, also related to the positioning is the fact that in order to produce optimal sectioning results, the Scorpion™ should be positioned perpendicular to the pipe longitudinal axis. If it was at some angle compared to the pipe, the LSC would not be positioned optimally resulting in a reduction of the penetration effect.

Although, there was no mean to verify the correct deployment of the system, difficulties to lower the Scorpion™ inside the pile were experienced and could have been instrumental to the incorrect deployment. Deployment is initiated by cutting the wire illustrated in Figure 2.4 with an explosive cutter. In the ESI test range, the Scorpion™ deployed correctly but the wire was sectioned manually. There is no apparent reason why the Scorpion™ would remain collapsed or partly collapsed when installed inside of a pile if the system function correctly. A valuable test to be performed would be to put a Scorpion™ with its charges in the collapse position along one side of a pipe and fire it to see the actual effect on pipe sectioning. The results of this test could be compared with those obtained in the Gulf of Mexico testing to ascertain that this is really what happened. A test plan would then be required to find the factors that could cause this faulty deployment of the Scorpion™ and resolve them. Some tests conditions could be a deformed pile, variable interior diameter of pile, presence of mud at level of deployment, effect of height of water, effect of friction between sliding items etc.

9.4.3 Blast pressure results

As indicated above, all the sensors did not work each time they were used. In the ESI test range, from an array of six sensors, two gave no signal in one experiment. In the Gulf testing from an array of twelve sensors, three did not work in one experiment and one in the other. All the sensors were verified and calibrated before those experiments, and even then, some did not work at all. This means that the condition of the experiment are very harsh and can cause faulty contacts that are cutting the signal. A possible solution could be to put two sensors at each position of the array. Then, during the use of the test charge in open water preceding the severing test, it would be possible to determine which sensor can give faulty results and keep this data for information only.

Using the DL 750 ScopeCorder connected to the sensor array, the shock wave pressures developed from the charges of the three piles in the structure of the first experiment were recorded. The data was then analyzed by Sonalysts and it can be found along with their preliminary conclusions given in their report in Annex I of the Background Documents[4] to this report. Since the results were very puzzling, a subsequent review of the data was performed and it was realized that some wrong assumptions have been done which influenced the results presented in Sonalysts report. Corrections were applied to the slant range distances and engineering charge weight. Those are discussed in Annex B and C as well as in Section 9.4.1 below. The charges and sensors arrangement is illustrated in Figure 9.7 below.

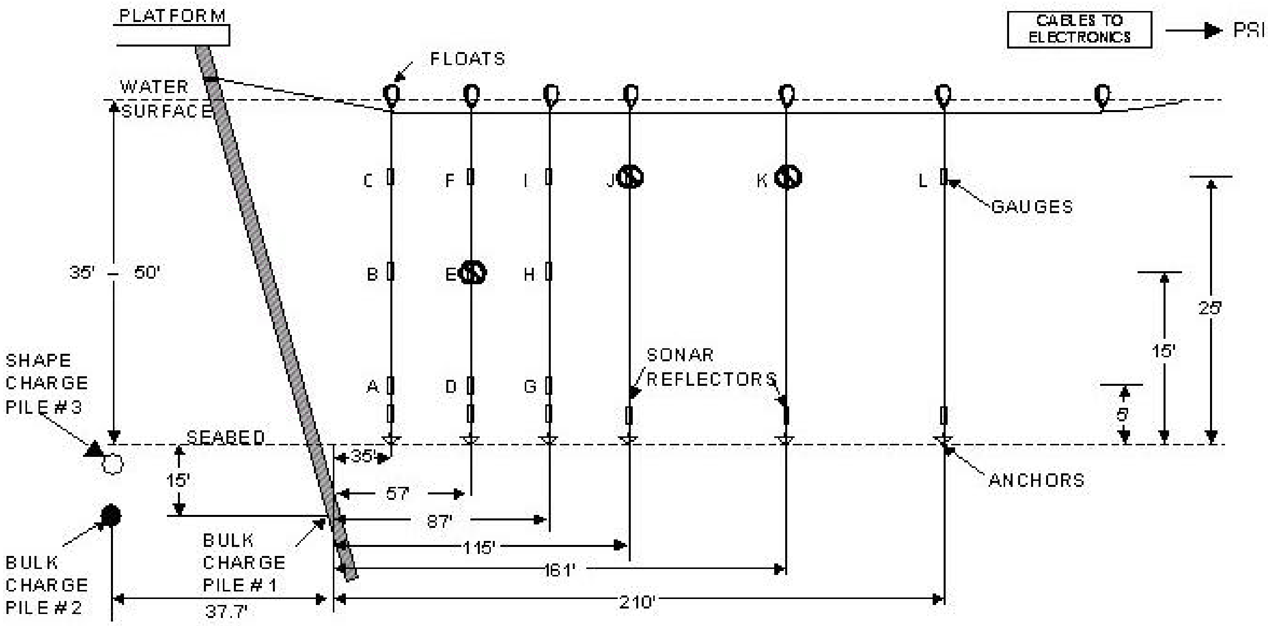


Figure 9.7 – Explosive charge and sensor array deployment

During the second test, blast pressure measurements were taken from the three severed piles and the well but an unfortunate error in the operation of the recording equipment resulted in the deletion of the recorded data instead of their storage. The operator took notes of the level of data he had observed before the deletion and indicated that the values were higher than those from the first experiment. This data is however too limited to be useful so it will not be possible to analyze measurements from the second experiment.

The recorded data of the blast pressure curves from the first experiment was first analyzed by Sonalysts experts and peak overpressure, impulse and energy flux density values were obtained from the recorded curves. These values and the method to obtain them will be explained later. The first review of the data did not lead to any conclusions because the data did not follow the generally accepted laws of shock wave physics and results tendency observed during tests done previously. A subsequent review by Mr. T.J. Broussard from the New Orleans MMS office led to the review of some assumptions made at the time of the testing and used in the calculation mainly the positions of the tested charge in the structure and their distance from the sensors in the array. His results led to more meaningful data review and they are presented in Annex K of the Background Documents[4] to this report. Subsequent review of these results by SNC TEC led to some adjustments to the results to consider the real weight of the engineered charge (4.05 lbs) compared to the used value of 4.6 lbs. Small changes were also made to obtain the exact value of the slant range or the distances between the blast charges and the sensors in the array. This final review and the method used to perform the calculations are presented in Annex B of this report.

In addition to the measured values, the values of peak overpressure, impulse and energy flux density were computed with the ARA model[7] for both types of charges (bulk and engineered) as explained in Annex B for comparison purposes. Since RDX was not in the choices of explosives in the calculator for this model, composition C-4 explosive was used for both types of charges.

Connor similitude equations coming from the so-called Connor study[8] and described in more details in Annex B were also used to compute the same values to compare with the experimental values and the ARA model results.

The blast overpressure values which are defined as the maximum initial excursion from ambient of the pressure gauge signal when the shock wave arrives[8] are presented in Table 9.2 below.

[7] Dzwilewski, P.T. and Fenton, G., *Shock Wave /Sound Propagation Modeling Results for Calculating Marine Protected Species Impact Zones During Explosive Removal of Offshore Structures*, Applied Research Associates Inc report for MMS contract 0302P057572, September 2003.
[8] Connor, J.G., *Underwater Blast Effects from Explosive Severance for Offshore Platform Legs and Well conductors*, Naval Surface Warfare Center, NAVSWC TR 90-532, 15 December 1990.

Table 9.2 – Measured and computed peak overpressure values

Peak Overpressure (psi)					
Transducer	Slant range (ft)	Charge weight (lb)	ARA UWC	Connor Main Pile SimEQ	Field measurements
Charge A (4.05lbs RDX engineered charge) – Pile 3					
A	77.2	4.05	155.7	42.0	139.2
B	80.9	4.05	147.0	38.4	140.3
C	85.1	4.05	138.2	34.8	78.8
D	98.6	4.05	115.5	26.2	86.7
F	104.5	4.05	107.6	23.4	74.4
G	127.7	4.05	84.3	15.9	45.5
H	129.6	4.05	82.8	15.5	93.2
I	132.3	4.05	80.7	14.9	119
L	251.6	4.05	36.8	4.3	10.1
Charge B (50lbs C4 bulk charge) – Pile 2					
A	77.2	50	465.7	205.1	137.9
B	80.9	50	439.9	190.3	167.1
C	85.1	50	413.5	172.7	98.2
D	98.6	50	345.5	130.5	90.9
F	104.5	50	321.9	116.8	134.2
G	127.7	50	252	79.6	64.1
H	129.6	50	247.5	77.3	82.7
I	132.3	50	241.4	74.4	118.8
L	251.6	50	110.2	21.6	26.8
Charge C (50lbs C4 bulk charge) – Pile 1					
A	40.3	50	1029.6	742.6	244.1
B	46	50	873.5	575.3	281.6
C	53.1	50	733.5	436.1	279
D	60.6	50	628.2	337.9	192.5
F	69.7	50	528.5	258.0	211.6
G	89.3	50	389.9	159.9	151.4
H	92.1	50	376	150.7	137.7
I	95.8	50	357.9	139.6	83.3
L	214.7	50	134.4	29.4	41.2

The second type of values considered are the impulse which is defined as the integral under the pressure-time signal[8]. Once again, impulse values were computed with the ARA model and the Connor similitude equations. As explained in Annex B, it is very important to remember that in his similitude equation for impulse, Connor used the reduced value of the impulse which he obtained by dividing the impulse value by the cube root of the charge weight in order to have the same type of equation as for the peak overpressure. In the case of the values presented in Table 9.3, the absolute values of impulse are used.

Table 9.3 – Measured and computed impulse values

Impulse (psi.s)					
Transducer	Slant range (ft)	Charge weight (lb)	ARA UWC	Connor Main Pile SimEQ	Field measurements
Charge A (4.05lbs RDX engineered charge) – Pile 3					
A	77.2	4.05	0.041	0.025	0.016
B	80.9	4.05	0.039	0.023	0.012
C	85.1	4.05	0.037	0.021	0.012
D	98.6	4.05	0.033	0.016	0.010
F	104.5	4.05	0.031	0.014	0.012
G	127.7	4.05	0.026	0.010	0.006
H	129.6	4.05	0.025	0.010	0.010
I	132.3	4.05	0.025	0.009	0.008
L	251.6	4.05	0.014	0.003	0.004
Charge B (50lbs C4 bulk charge) – Pile 2					
A	77.2	50	0.226	0.237	0.069
B	80.9	50	0.216	0.221	0.017
C	85.1	50	0.207	0.202	0.013
D	98.6	50	0.181	0.156	0.054
F	104.5	50	0.171	0.140	0.019
G	127.7	50	0.143	0.098	0.054
H	129.6	50	0.141	0.096	0.013
I	132.3	50	0.138	0.093	0.016
L	251.6	50	0.077	0.029	0.022
Charge C (50lbs C4 bulk charge) – Pile 1					
A	40.3	50	0.781	0.140	0.146
B	46	50	0.616	0.193	0.126
C	53.1	50	0.477	0.183	0.108
D	60.6	50	0.376	0.108	0.093
F	69.7	50	0.293	0.018	0.080
G	89.3	50	0.188	0.081	0.061
H	92.1	50	0.178	0.066	0.059
I	95.8	50	0.166	0.044	0.056
L	214.7	50	0.039	0.030	0.023

The last type of values considered are the energy flux densities which is defined as the integral of the square of the pressure amplitude [8]. Once again, energy flux density values were computed with the ARA model and the Connor similitude equations. As explained in Annex B, it is very important to remember that, like in the case of the impulse, Connor used in his similitude equation for energy flux density the reduced value of the energy flux density which he obtained by dividing the energy flux density value by the cube root of the charge weight in order to have the same type of equation as for the peak overpressure. In the case of the values presented in Table 9.4, the absolute values of energy flux density are used.

Table 9.4 - Measured and computed energy flux density values

Energy Flux Density (psi.in)					
Transducer	Slant range (ft)	Charge weight (lb)	ARA UWC	Connor Main Pile SimEQ	Field measurements
Charge A (4.05lbs RDX engineered charge) – Pile 3					
A	77.2	4.05	0.586	0.101	0.132
B	80.9	4.05	0.531	0.087	0.097
C	85.1	4.05	0.478	0.074	0.055
D	98.6	4.05	0.352	0.047	0.038
F	104.5	4.05	0.312	0.039	0.054
G	127.7	4.05	0.206	0.021	0.013
H	129.6	4.05	0.199	0.020	0.057
I	132.3	4.05	0.191	0.019	0.054
L	251.6	4.05	0.050	0.002	0.004
Charge B (50lbs C4 bulk charge) – Pile 2					
A	77.2	50	9.314	3.045	0.813
B	80.9	50	8.449	2.697	0.138
C	85.1	50	7.605	2.305	0.078
D	98.6	50	5.599	1.463	0.419
F	104.5	50	4.961	1.221	0.105
G	127.7	50	3.269	0.656	0.280
H	129.6	50	3.170	0.626	0.047
I	132.3	50	3.037	0.589	0.082
L	251.6	50	0.798	0.079	0.051
Charge C (50lbs C4 bulk charge) – Pile 1					
A	40.3	50	24.539	3.589	4.168
B	46	50	16.219	5.526	2.996
C	53.1	50	10.349	4.353	2.094
D	60.6	50	6.844	1.756	1.506
F	69.7	50	4.417	0.162	1.062
G	89.3	50	2.034	1.009	0.573
H	92.1	50	1.846	0.678	0.530
I	95.8	50	1.632	0.259	0.480
L	214.7	50	0.131	0.090	0.064

9.4.4 Blast pressure results analysis

A complete review of the peak overpressure measured data was performed and the details are given in Annex C of this report. As it can be seen in Table 9.2, some of the peak overpressure data do not follow the physics of shock waves, such as sensor G from engineered charge which pressure value is half the sensor H value which is further away to the blast. Another example of this is observed with sensors G, H and I from bulk charge # 1 which show decreasing values with increasing slant range, as expected, while at the same moment, values from bulk charge # 2 with the same sensors show increasing values with increasing distances. The possibility of having signals of some sensors partly interrupted should be considered.

As can be observed in Table 9.2, the peak overpressure obtained from the engineered charges system are generally lower when compared to measured values with the bulk charges at the same distance from the sensors. The values obtained from the bulk charge closer to the sensor array (Charge C) are generally higher in comparison to the other bulk charge. Both of these results are in accordance with shock wave physics.

The peak overpressure measured values along with the computed values obtained with ARA model and the Connor similitude equation were first put in graphs as a function of slant range as was done by Broussard. These graphs are presented in Annex B. It was eventually decided to combine the results from both bulk charges (which are at different distances from the sensors). In addition, the data is also presented in a log-log graph as a function of the range divided by the cube root of the charge weight, as was done by Connor[8]. The graph obtained is shown in Figure 9.8 below.

As can be observed in both Table 9.2 and Figure 9.8, ARA model gives generally higher computed values than experimental measures and Connor similitude equations for the engineered charge. This is an indication that the ARA model, which was established based on assumptions made from theoretical considerations and computer simulations, is more conservative. On the other hand, the Connor similitude equation gives much lower computed values of peak overpressure for the engineered charge. Connor similitude equation was obtained from linear regression done on actual composition B charge data, a less powerful explosive than RDX which could explain part of the difference. In addition, the important scatter of the data shown in Figure 9.8 and the rather low value of regression coefficient value of 0.74 bring us to put some caution on the conclusions which can be made with the experimental data.

In the case of the two bulk charges experimental data which was grouped together, it can also be observed that the ARA model produces much higher values of peak overpressure which confirms that the ARA model is more conservative. Figure 9.8 shows that the curve obtained with Connor similitude equation data is closer to the experimental measurements. Since composition B explosive has a power very similar to composition C4, this partly confirms the comment made above. The scattering of data around the linear regression line and the higher regression coefficient makes us more confident on this data.

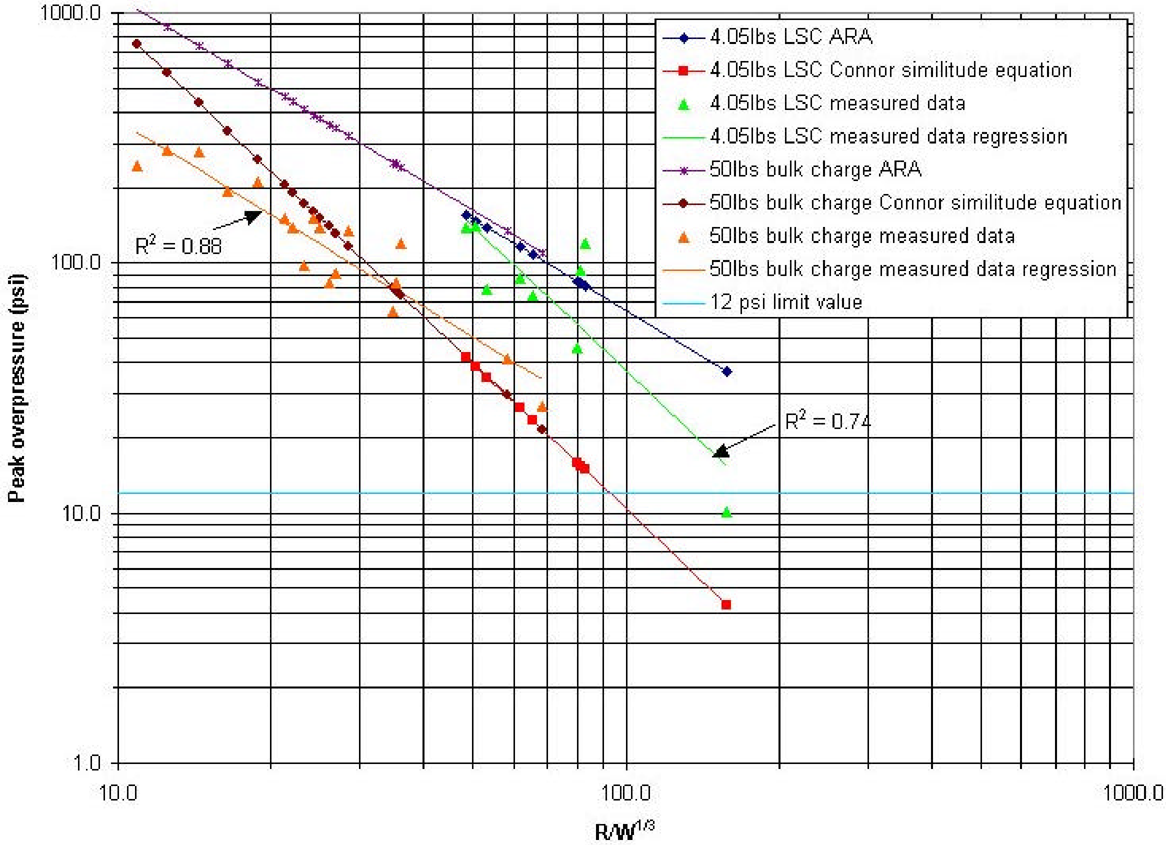


Figure 9.8 – Peak overpressure data

The figure also presents the 12 psi peak overpressure criteria for marine mammal harassment as per NOAA 50 CFR Part 216[9]. From the regression, the distance from the explosive charges corresponding to this 12 psi limit value was computed for both charges using the linear regression curve equations presented in Annex B. The coefficients of regression obtained with these equations are considered low so the equations are not presented here. A value of 286.5 feet for the engineered charge and 585.1 feet for the bulk charge have been computed indicating a reduction factor of 2.04 from going from the bulk charge to the engineered charge. Considering the generally accepted rule to compare explosives based on the cube root of the equivalent weight of explosive mentioned by Cooper[10] and using TNT as the reference explosive, a reduction factor of 2.17 was computed. This value was obtained considering that composition C4 and RDX have values respectively of 1.5 and 1.82 times the value of TNT detonation

[9] Department of Commerce, National Oceanic and Atmospheric Administration, **50 CFR Part 216**, Taking and Importing Marine Mammals; Taking Marine Mammals Incidental to Naval Activities, Final rule, [Federal Register: May 4, 2001 (Volume 66, Number 87)], [Rules and Regulations], [Page 22450-22467]
[10] Cooper, P.W., *Explosives Engineering*, VCH Publishers Inc, New-York, NY, 1996.

pressure. This means that a reduction of the charge weight by a factor of about 10 leads to a reduction of the harassment zone by a factor of about 2.

The second parameter considered to compare the two charges, as indicated above is the impulse. Data presented in Table 9.3 and Figure 9.9 below show that for this parameter, both ARA model and Connor similitude equation computed values are higher than the measured values for the engineered charge. Once again the values are closer to the Connor similitude equation. The ARA model gives much higher values confirming that it is more conservative. While the regression coefficient on the line obtained with the experimental data is better than for the peak overpressure, there is still some important scatter.

The impulse results obtained with the bulk charge are interesting because they tend to show that for larger explosive weights, the ARA model and the Connor similitude equation are close to each other. The comparison with the experimental data is not as good however as shown by the large scatter of the data and the very low value of the linear regression coefficient (0.39) obtained.

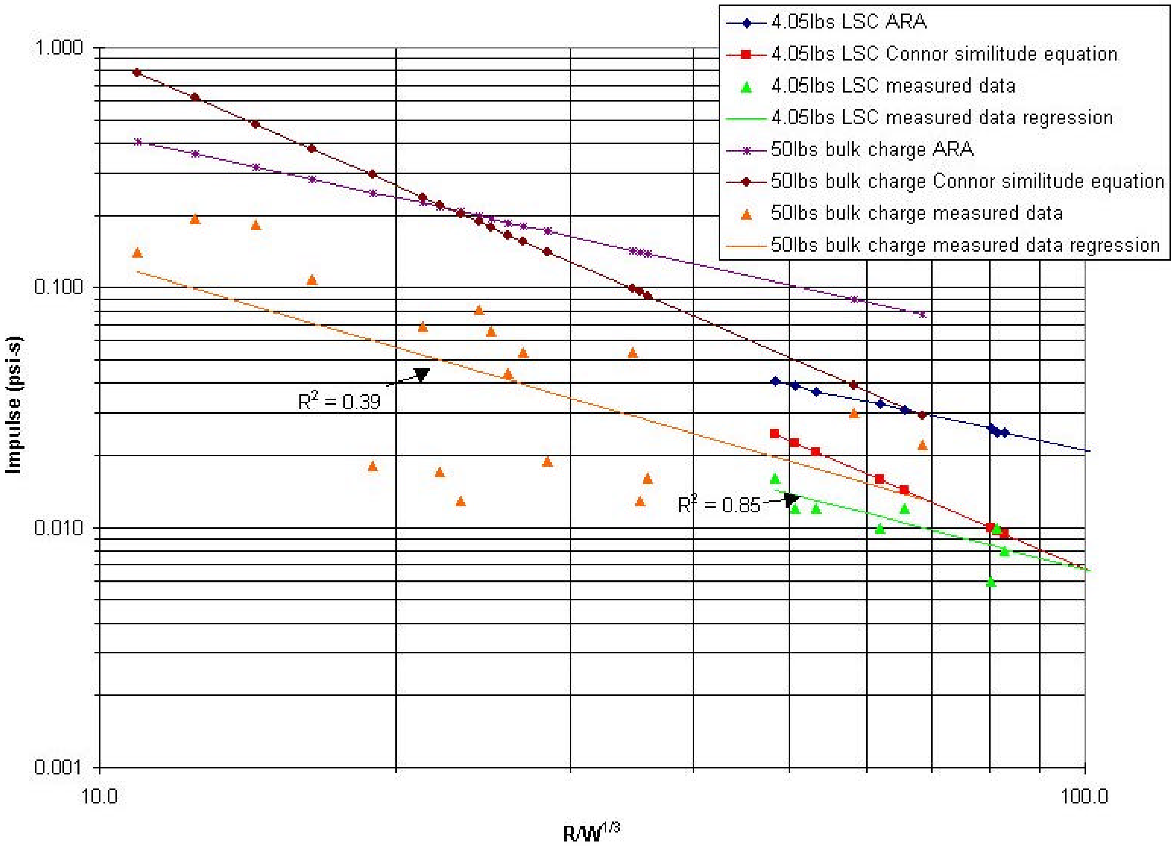


Figure 9.9 - Impulse data

The last factor considered was the energy flux density. Data presented in Table 9.4 and in Figure 9.10 below show once again for both types of charges that the ARA model produces higher values than the experimental ones hence confirming that it is more conservative. Because of the small regression coefficients obtained the scatter of the data around the line obtained, we do not feel confident to give a comparison factor however.

The Connor similitude equation seems to match the experimental data very well for the engineered charge but once again some caution must be used. The similitude equation results obtained for the bulk charges are higher than the experimentally measured data but, like in the case of the impulse, the scattering of the data is very important.

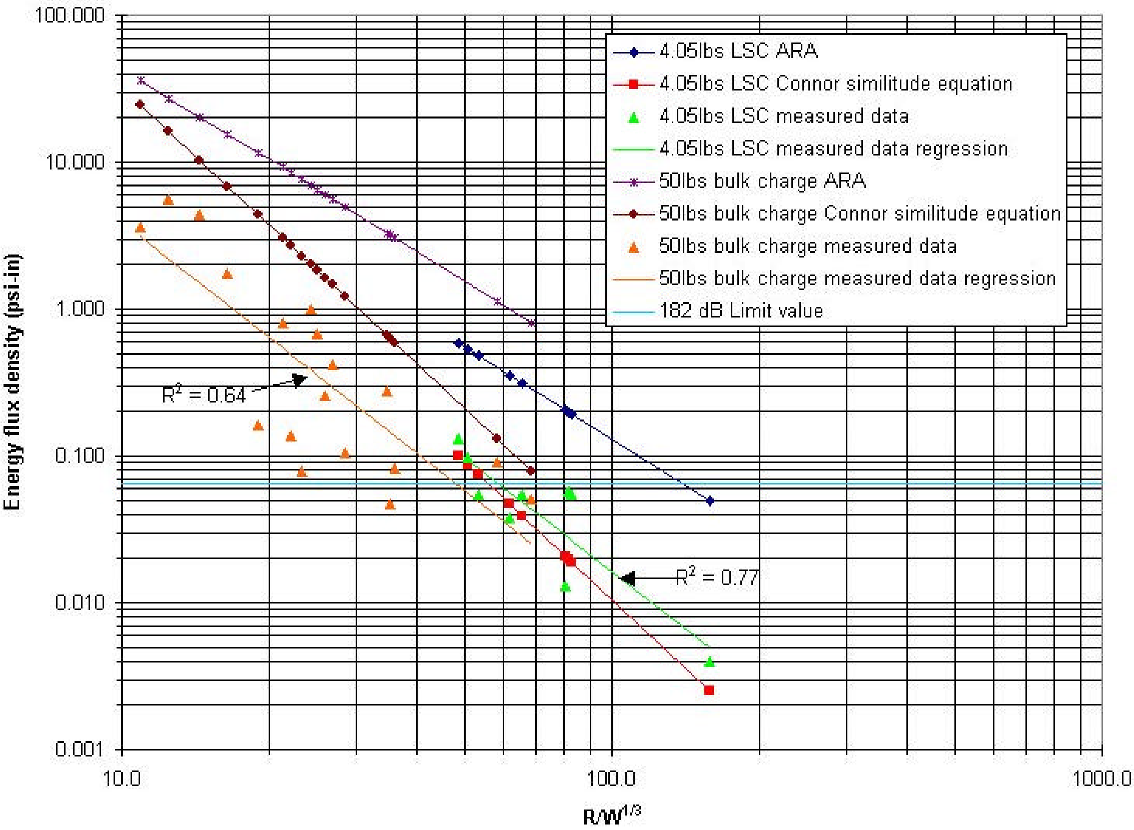


Figure 9.10 - Energy flux density data

This brings the second criteria for marine mammal harassment that consist of an energy-based temporary threshold shift (TTS) of 182 dB (re 1 µPa^2·sec) (ref NOAA 50 CFR Part 216[9]). Then to apply this criteria for marine mammal harassment of 182 dB re 1 µPa^2·sec for any 1/3 octave band, we used some assumptions from ARA study. These assumptions permitted to find out that 182 dB re 1 µPa^2·sec for any 1/3 octave band corresponds to 192.4 dB re 1 µPa^2·sec of total energy flux density, which in turns corresponds to 0.01135KPa-m or 0.06489 psi-in. Linear regression led to the equations represented as the data regression curves in Figure 9.10 and detailed in Annex B. However, the low value of regression coefficients led us to avoid to put these equations in the main part of this report. Still the equations were used to compute the distances corresponding to the 182 dB threshold and values of 93.2 feet for the engineered charge and 176.1 feet for the bulk charge were obtained. This means that a reduction factor of 1.89 is obtained from going from the bulk charge to the engineered charge. This value is close to

2 like in the case of the peak overpressure. Our literature search did not lead to a factor which would be equivalent to the detonation pressure and enable comparisons like we did in the peak overpressure. It is interesting to note that this threshold led to distance values from the explosive charges which are about one third of the values obtained for the peak overpressure. Therefore in our case the peak overpressure appear to be the more restrictive factor.

In summary, the experimental data obtained during this program are very limited and lead to large scatter of the data and small regression coefficients compared to what has been obtained by Connor from his experimental work. Therefore some caution must be used if one wants to make definitive conclusions from the data obtained. It is believed that additional experiments would be very useful to confirm the results obtained for both types of charges studied. Still, although we do not want to put a definite number on it, it appears very clear that the ARA model is conservative in its predictions.

10.0 - CONCLUSIONS

The results of the studies presented in this report lead us to make the following conclusions:

- An engineered charge based on the linear shaped charge principle was developed using computer simulations and including verification of the optimal values of the parameters for this design.
- A commercially available linear shaped charge produced by Accurate Energetics containing pressed RDX explosive in a copper sheath was found to meet the optimum criteria of the engineered charge design obtained by computer simulation.
- A hollow structural steel casing to be used as the linear shape charge container was tested and proved sturdy enough for the intended use. Ancillary parts (charge holding device and booster system) were developed to ensure correct functioning of the charge system.
- The selected linear shape charge enclosed in its watertight casing and fitted in a manually deployed Scorpion™ system has been demonstrated efficient in severing submerged piles 30"ø, 1" thickness wall and 48"ø, 1.5" thickness wall at the ESI test range. Although the complete charge system was not produced, it has been shown that such a system could be manufactured for piles with a diameter as low as 24".
- The total charge weight to severe a 48"ø pile with 1.5" thick wall is 6.58 pounds. For the 30"ø pile with 1" thickness wall, the charge weight is 4.05 pounds. Those values are much lower than the 50 pounds bulk charge and close to the generics consultation limit.
- The Scorpion-2, while providing remote operation and more safety for the operators for the deployment of the system in the pipe to be severed, appeared not to deploy properly when used in actual structures in the Gulf of Mexico with the engineered charges, based on the fact that only partial sectioning of piles was obtained during testing.
- Peak overpressure, impulse and energy flux density from engineered and bulk charges follow the accepted exponential shape when presented as a function of the slant range distance divided by the cube root of the charge weight.
- Generally the experimental values fit more closely to those calculated with Connor similitude equation than those obtained with ARA model.
- Use of an engineered linear shape charge fitted inside a pile produced a reduced blast overpressure leading to about one half of the harassment zone compared to the composition C4 50 pounds bulk charge based on a limit value of 12 psi. This reduction level corresponds well to what is expected from the comparison of the cube root weight

of the equivalent explosive weight. The exact reduction level would require additional testing because some of the data obtained did not appear to follow the physics laws relating to the reduction of intensity with distance from the blast source, as illustrated with data calculated with the ARA model.

- Use of an engineered linear shape charge fitted inside a pile produced a reduced energy flux density also resulting in approximately half the harassment zone of the 50 pounds bulk charge based on a limit value of 182 dB (re 1 $\mu Pa^2 \cdot sec$). The exact reduction level would require additional testing because following the calculation on the data the energy flux density values are scattered.

- With the explosive considered (type and weight), the more stringent factor for marine mammal harassment zone definition appears to be peak overpressure in our case.

11.0 - FUTURE WORK

The results obtained also indicated that additional work could be performed to complete what has been achieved in this research program.

- Although the preliminary results obtained from the tests performed in a quarry lake proved that the engineered charge system was working fine, the testing in the Gulf of Mexico showed some problems with the Scorpion™ deployment. It would be interesting to do additional work on the Scorpion™ design to ensure perfect deployment all the time in all the arrangements of piles. The test series mentioned in Section 9.4 would enable to prove that the problem comes from the Scorpion™ deployment and then to carry on tests to ascertain that it could be improved.

- It would also be valuable to study improvement to the degree of collapsing of the Scorpion™ to reduce the size of the collapsed system to facilitate positioning.

- Once the charge system problem is solved, additional work should be done to perform severing of piles of 30" and 48" diameter from structures in the Gulf of Mexico.

- The measurements of blast overpressure in the Gulf of Mexico testing were not fully reliable. Some sensors did not function, certain values of peak overpressures are questionable. Due to some problems with the sonar, it was not possible to locate the sensors in one experiment.

    1. To address the questionable values of sensors the procedure should be reviewed and be tried with small explosive charges in free water with the idea of adding back-up sensors before using it again in structure piles. It could then become easier to avoid unexpected situations and, if needed, reject values on the ground of this understanding in future tests.

2. Close attention should be given to peak overpressure propagation on subsequent experiments to understand what happened in the tests to produce the questionable results.

3. Localization of the array should be reliable to get valuable values. A review of the sonar features should be done.

- More experimental data should enable to obtain regression equations for peak overpressure, impulse and energy flux density with better regression coefficient and then permit to appreciate more closely the application of ARA model and Connor similitude equations.

- Additional tests with different types of explosives should be performed to enable the checking of the influence of the explosive detonation properties. This would also bring the possibility to be able to obtain general similitude equations which would be applicable to the different explosive through a correction factor applied to a reference explosive weight.

12.0 - REFERENCES

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[8] Connor, J.G., *Underwater Blast Effects from Explosive Severance for Offshore Platform Legs and Well conductors*, Naval Surface Warfare Center, NAVSWC TR 90-532, 15 December 1990.

[9] Department of Commerce, National Oceanic and Atmospheric Administration, **50 CFR Part 216**, Taking and Importing Marine Mammals; Taking Marine Mammals Incidental to Naval Activities, Final rule, [Federal Register: May 4, 2001 (Volume 66, Number 87)], [Rules and Regulations], [Page 22450-22467]

[10] Cooper, P.W., *Explosives Engineering*, VCH Publishers Inc, New-York, NY, 1996.

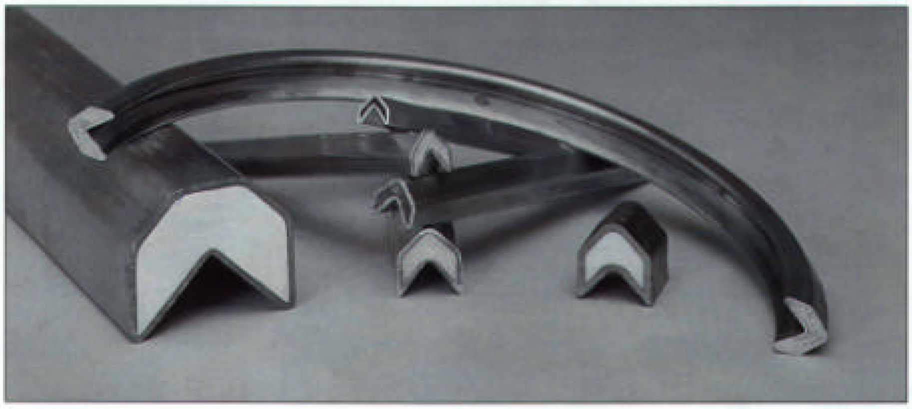
Annex A

Accurate Energetics linear shaped charge data

The Accurate Companies

TECHNICAL DATA

LINEAR SHAPED CHARGE



Description

Accurate's Linear Shaped Charge (LSC) is an explosive enclosed in a seamless metal sheath and fabricated in continuous lengths shaped in the form of an inverted "V."

When detonated, the V-shaped metal liner with explosive core produces a uniform linear cutting action. This cutting action, known as the "Monroe effect," can be accentuated by controlling LSC dimensions and configuration, explosive type and load, liner thickness, and continuity.

At detonation, the focusing of the explosive high pressure wave as it becomes incident to the side wall causes the metal liner of the LSC to collapse—creating the cutting force. If the standoff distance is optimum, collapse of the liner will be complete before it reaches the target as a plasma jet. This high velocity jet impacts the target with pressures exceeding the target's yield strength and literally pushes the target material to either side of the path of the jet.

The liner may be formed using any malleable metal, but is typically copper, aluminum, lead or silver. Copper is generally used with most large core loads, but for some applications, Aluminum is recommended to provide structural integrity. For small core loads where flexibility is required, Lead is preferred, while Silver is reserved primarily for use with thermally-resistant explosive core loads.

The explosive core loads commonly used in Accurate's LSC are RDX, HMX, PETN, HNS and PYX. The detonation rates for each are as follows:

RDX: 8,200 meters/second @ 1.65 g/cc.
HMX: 9,100 meters/second @ 1.84 g/cc.
PETN: 8,300 meters/second @ 1.7 g/cc.
HNS: 6,900 meters/second @ 1.6 g/cc.
PYX: 7,200 meters/second @ 1.68 g/cc.

Performance

The cutting ability of LSC is affected by a number of variables, including the detonation rate of the explosive core load, the characteristics of the metal liners, and the density of the material being cut.

There is, however, a general scaling guide which may be used to determine the penetration as related to core load, in that penetration of a given material is essentially proportional to the square root of the core load. The formula is as follows:

$$T_1 = T_2 \sqrt{\frac{W_1}{W_2}}$$

T_1 = unknown penetration depth
T_2 = recorded penetration by W_2 core load
W_1 = select core load
W_2 = recorded core load

Please recognize that all analytical comparisons and reported data were obtained under controlled test conditions and should be considered as relative only.

Accurate does not assume any liability whatsoever for the accuracy or completeness of the information contained herein. Although the recommendations stated are based upon tests and the best information available to us, it is expressly understood that we make no guarantee of results, and assume no responsibility or liability in connection with the use of our products. Nothing contained herein shall be construed as an offer to supply a product or to constitute a license, implied or otherwise, to use our product in the infringement of any patent, whether owned by The Accurate Companies or others.

The Accurate Companies

CHARACTERISTICS

LINEAR SHAPED CHARGE

Copper LSC

*Core Load Grains/Foot**	*Width** (In.)*	*Height** (In.)*	*Approx. Gross Weight (Lbs./Ft.)*	*Approx. Standoff (In.)*	*Penetration† at Optimum Standoff (In.)*
100	.28	.25	.07	.20	.25
150	.35	.31	.20	.20	.30
250	.45	.38	.22	.35	.40
400	.48	.53	.31	.37	.55
600	.68	.58	.51	.60	.70
900	.76	.68	.70	.66	.85
1,200	.89	.92	.96	.75	1.00
2,000	1.15	1.04	1.31	.75	1.50
3,200	1.43	1.23	1.66	1.00	1.70
4,400	1.81	1.41	2.50	1.25	2.25
10,500	2.56	1.78	4.30	2.00	3.50

Cast LSC

In addition to formed Linear Shaped Charge, Accurate offers a Cast LSC in various lengths and explosive weights. Length and configuration can be manufactured to meet most needs. Popular applications for cast charges include oil well control situations and for cutting heavy-walled steel structures. Cast LSC can be manufactured with either steel or aluminum housings, and can be poured with a variety of explosives to include Octol, Composition B and Hexolite.

Aluminum LSC with core loads of 22-400 grains/foot are available on request.
**Explosive Core Loading tolerance is ±10%.*
***Dimensional tolerance is ± .020.*
†Performance shown is for RDX explosive into 1018 mild steel.

Y 0 0 0 – 0

Grain Load Per Foot			
Core Material	0-RDX	2-CH-6	4-HMX
	1-PETN	3-HNS	5-PYX
Sheath Material	0-Lead	2-Aluminum	4-Pewter
	1-Silver	3-Copper	
Product Type	2-Linear Shaped Charge (LSC)		

Example: Y230-200 is a Linear Shaped Charge with a copper sheath and 200 grains/foot of RDX core.

The Accurate Companies

5891 Hwy. 230 West, McEwen, TN 37101 • (931) 729-4207• (800) 416-3006 • fax (931) 729-4211

Annex B

Connor-ARA UWC-In-Situ Comparisons

Connor-ARA UWC-In-Situ Comparisons

P. Pelletier
D. Saint-Arnaud
SNC TEC

14 May 2004

Introduction

This document is a modified version of the document "Conner-ARA UWC-In-Situ Comparisons" prepared by Mr. T.J. Broussard from the New Orleans office taking into consideration some differences between the reported and actual values for the charge weight and set-up distances as well as some differences in the equations used for the impulse and energy flux density.

Calculation methods and differences

Physical differences

The engineered charge weight had been reported in the past as being 4.6 pounds and it was planned to mention it in SNC TEC Corp. final report that the actual weight is 4.05 pounds. The difference comes from that the linear shape charge (LSC) used to produce the engineered charge was originally planned to 4400 grains/foot but it was eventually changed to 4000 grains/foot by Accurate Energetics, the charge supplier. While this change has been done prior to the tests performed at DRDC Suffield, we kept using the old number.

We found a small mistake in the calculation of the slant range coming from the calculation of the distance in the horizontal plane. Figure 1 below illustrates the situation. In the calculation of the slant range the horizontal plane distance used by Broussard was obtained by adding 37.7 feet to the distance between transducer of interest and pile 1 to which the transducer array was tied. According to the drawing received at SNC TEC describing the set-up, the 37.7 feet distance represents the distance shown in Figure B.1. Therefore , in order to obtain the actual distance in the horizontal plane ("y"), we have to obtain the distance "a". We considered the platform arrangement to be a equilateral triangle and from trigonometry, the value of distance was computed as being 21.67 feet. From this we computed the distance "y" for all the transducers and eventually the modified slant distance by considering the distance in the vertical plane. The modified values are presented in the tables presented in this document. The difference between those values and the values computed by Broussard are about 2 feet.

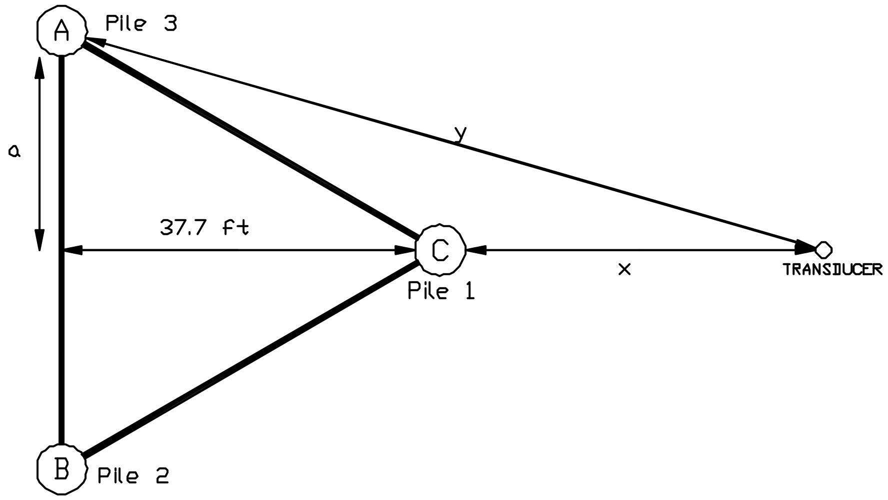


Figure B.1 – Platform and transducers considered arrangement

Connor similitude equations differences
In his calculations of impulse and energy flux density, Broussard used the equations for reduced impulse and reduced energy flux given in page 6-3 of from Connor study[11] and presented below:

$$I/W^{1/3} = 15.35\left(R/W^{1/3}\right)^{-1.79} \tag{1}$$

$$E/W^{1/3} = 11900\left(R/W^{1/3}\right)^{-3.13} \tag{2}$$

The computed results reported in his tables for the "Connor Main Pile SimEQ" are found to be the reduced values of impulse and energy flux density divided by the cube root of the charge weight rather than the actual values of impulse and energy flux density. These latter values are used for the ARA model and the measured values.

<u>ARA model calculations</u>
The bulk charges used in this program were made of composition C4 explosive. The calculations were performed using the calculator (EXCEL® version) supplied by MMS based on ARA report[12] considering the modified distances discussed above and C4 explosive for the bulk charge. In the case of the engineered charge, the RDX explosive was not available and we could not find acceptable details on the "user explosive" neither a way to adjust the parameters used for a user defined one. We looked at the other explosives but we were surprised to see that explosives which are known to have lower detonation pressure than C4

[11] Connor, J.G., *Underwater Blast Effects from Explosive Severance for Offshore Platform Legs and Well conductors*, Naval Surface Warfare Center, NAVSWC TR 90-532, 15 December 1990.
[12] Dzwilewski, P.T. and Fenton, G., *Shock Wave /Sound Propagation Modeling Results for Calculating Marine Protected Species Impact Zones During Explosive Removal of Offshore Structures,* Applied Research Associates Inc report for MMS contract 0302P057572, September 2003.

produced higher peak overpressure based on the ARA model. Since a review of the ARA model is out of the scope of our research project, it was decided to use C4 explosive for the engineered charge. The value to be used for the time constant multiplier and the method to select it was not clear to us so we used the default value of 6.7.

Results

Peak overpressure

Table B.1 – Peak overpressure data

Peak Overpressure (psi)					
Transducer	Slant range (ft)	Charge weight (lb)	ARA UWC	Connor Main Pile SimEQ	Field measure
Charge A (4.05lbs RDX engineered charge) – Pile 3					
A	77.2	4.05	155.7	42.0	139.2
B	80.9	4.05	147.0	38.4	140.3
C	85.1	4.05	138.2	34.8	78.8
D	98.6	4.05	115.5	26.2	86.7
F	104.5	4.05	107.6	23.4	74.4
G	127.7	4.05	84.3	15.9	45.5
H	129.6	4.05	82.8	15.5	93.2
I	132.3	4.05	80.7	14.9	119
L	251.6	4.05	36.8	4.3	10.1
Charge B (50lbs C4 bulk charge) – Pile 2					
A	77.2	50	465.7	205.1	137.9
B	80.9	50	439.9	190.3	167.1
C	85.1	50	413.5	172.7	98.2
D	98.6	50	345.5	130.5	90.9
F	104.5	50	321.9	116.8	134.2
G	127.7	50	252	79.6	64.1
H	129.6	50	247.5	77.3	82.7
I	132.3	50	241.4	74.4	118.8
L	251.6	50	110.2	21.6	26.8
Charge C (50lbs C4 bulk charge) – Pile 1					
A	40.3	50	1029.6	742.6	244.1
B	46	50	873.5	575.3	281.6
C	53.1	50	733.5	436.1	279
D	60.6	50	628.2	337.9	192.5
F	69.7	50	528.5	258.0	211.6
G	89.3	50	389.9	159.9	151.4
H	92.1	50	376	150.7	137.7
I	95.8	50	357.9	139.6	83.3
L	214.7	50	134.4	29.4	41.2

The peak overpressure data were put in graphs the same way as Broussard but it was found that presentation of the data as a function of the factor "$R/W^{1/3}$" and using log-log graph was giving a better view of the data. In the case of the bulk charges, the data was combined on one chart because the only difference came from the slant range from the transducers.

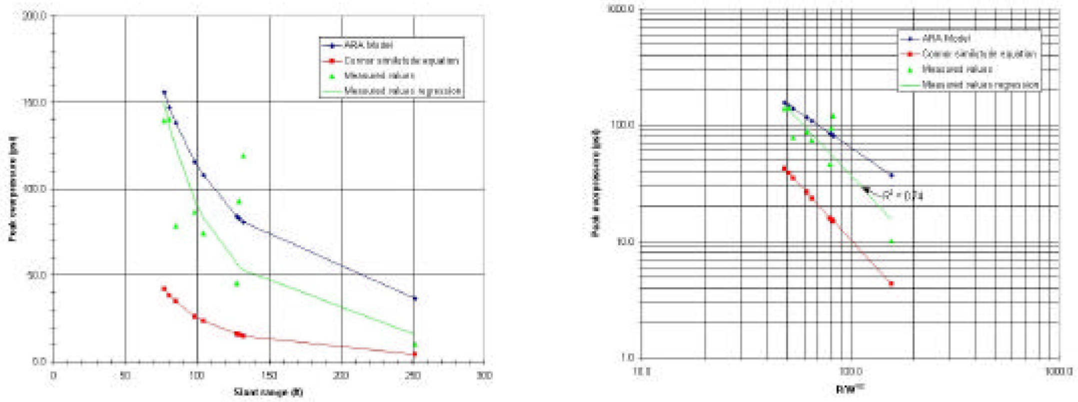


Figure B.2 – Peak overpressure – 4.05 lbs engineered charge

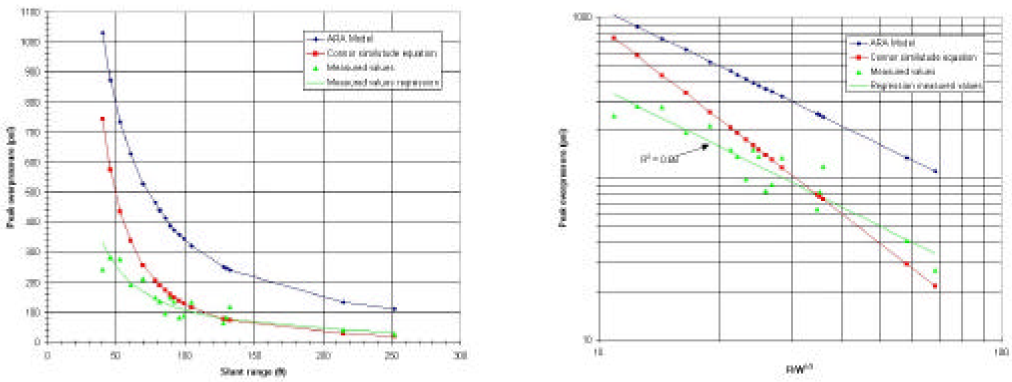


Figure B.3 – Peak overpressure – Combined 50 lbs bulk charges data

Using linear regression, we computed the equations for the measured data from both types of charge with the least square method in an EXCEL® spreadsheet. The equation obtained for the 4.05 lbs engineered charge was:

$$P = 260581 \left(R/W^{1/3}\right)^{-1.923} \tag{3}$$

with a regression coefficient (R^2) of 0.74. This value of regression coefficient is considered low and can be easily explained when looking at the dispersion of the data around the line in the right side of Figure B.2. Using the data from both bulk 50 lbs bulk charges tested, the following equation was obtained:

$$P = 6473.06 \left(R / W^{1/3} \right)^{-1.241} \qquad (4)$$

with a regression coefficient (R^2) of 0.88. This value of regression coefficient is much better and while there is still some dispersion of the data, the fact that we have more data covering a larger range of distance helps in reducing the regression coefficient. This also indicates that having more experimental data should be useful to define more exactly the actual equation.

Both charges experimental data as well as the Connor similitude equations and ARA model are illustrated in Figure B.4 below. Only the log-log graph of the data as a function of "$R/W^{1/3}$" was used.

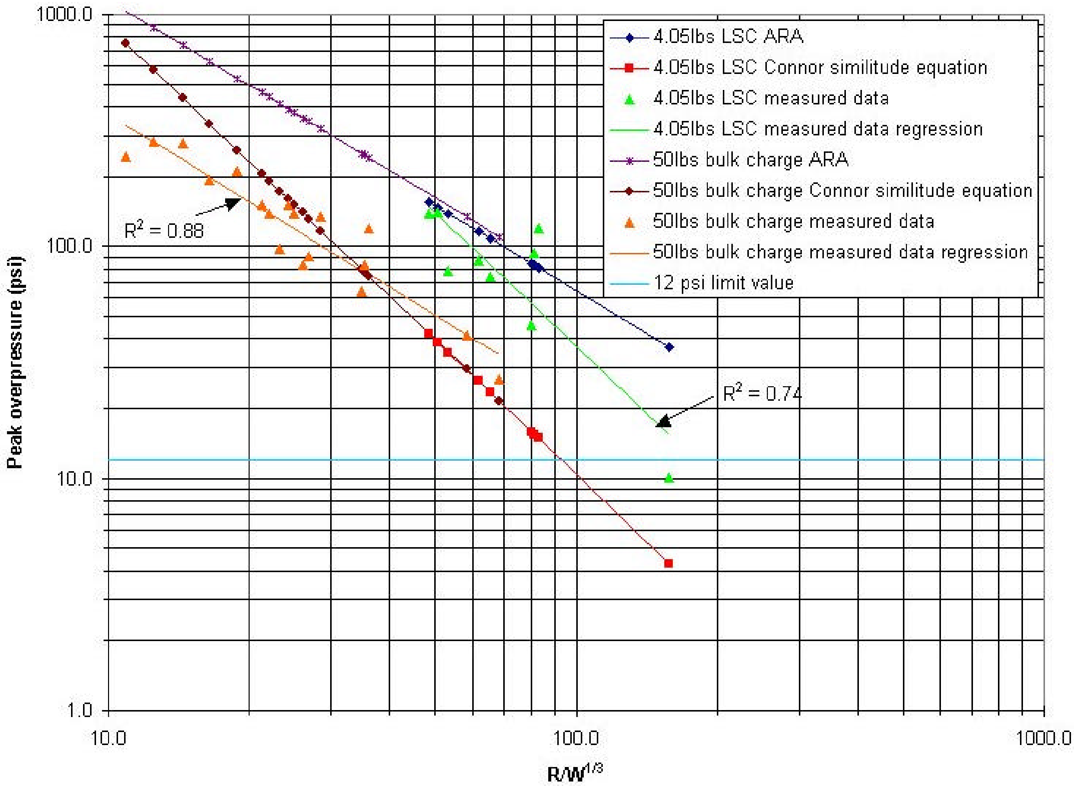


Figure B.4 – Peak overpressure – data from both types of charges

The figure also presents the 12 psi peak overpressure criteria for marine mammal harassment as per NOAA 50 CFR Part 216. From equations (3) and (4), the range distance corresponding to this 12 psi limit value was computed for both charges. A value of 286.5 feet for the engineered charge and 585.1 feet for the bulk charge so a reduction factor of 2.04 is obtained when going from the bulk charge to the engineered charge.

Impulse

The impulse values computed by Sonalysts were compared to the values obtained from the ARA model and the Connor similitude equation presented as equation (1). The data obtained are given in Table B.2.

Table B.2 – Impulse data

Impulse (psi-s)					
Transducer	Slant range (ft)	Charge weight (lb)	ARA UWC	Connor Main Pile SimEQ	Field measure
Charge A (4.05lbs RDX engineered charge) – Pile 3					
A	77.2	4.05	0.041	0.025	0.016
B	80.9	4.05	0.039	0.023	0.012
C	85.1	4.05	0.037	0.021	0.012
D	98.6	4.05	0.033	0.016	0.010
F	104.5	4.05	0.031	0.014	0.012
G	127.7	4.05	0.026	0.010	0.006
H	129.6	4.05	0.025	0.010	0.010
I	132.3	4.05	0.025	0.009	0.008
L	251.6	4.05	0.014	0.003	0.004
Charge B (50lbs C4 bulk charge) – Pile 2					
A	77.2	50	0.226	0.237	0.069
B	80.9	50	0.216	0.221	0.017
C	85.1	50	0.207	0.202	0.013
D	98.6	50	0.181	0.156	0.054
F	104.5	50	0.171	0.140	0.019
G	127.7	50	0.143	0.098	0.054
H	129.6	50	0.141	0.096	0.013
I	132.3	50	0.138	0.093	0.016
L	251.6	50	0.077	0.029	0.022
Charge C (50lbs C4 bulk charge) – Pile 1					
A	40.3	50	0.781	0.140	0.146
B	46	50	0.616	0.193	0.126
C	53.1	50	0.477	0.183	0.108
D	60.6	50	0.376	0.108	0.093
F	69.7	50	0.293	0.018	0.080
G	89.3	50	0.188	0.081	0.061
H	92.1	50	0.178	0.066	0.059
I	95.8	50	0.166	0.044	0.056
L	214.7	50	0.039	0.030	0.023

The impulse data for Connor similitude equation was obtained using equation (1) above and the ARA model data was obtained using the EXCEL® spreadsheet calculator. As in the case of the peak overpressure, we prepared two types of graphs for each charge, one of the impulse as a function of the slant range using linear axis like Broussard and one with the data as a function of $R/W^{1/3}$ with log-log axis.

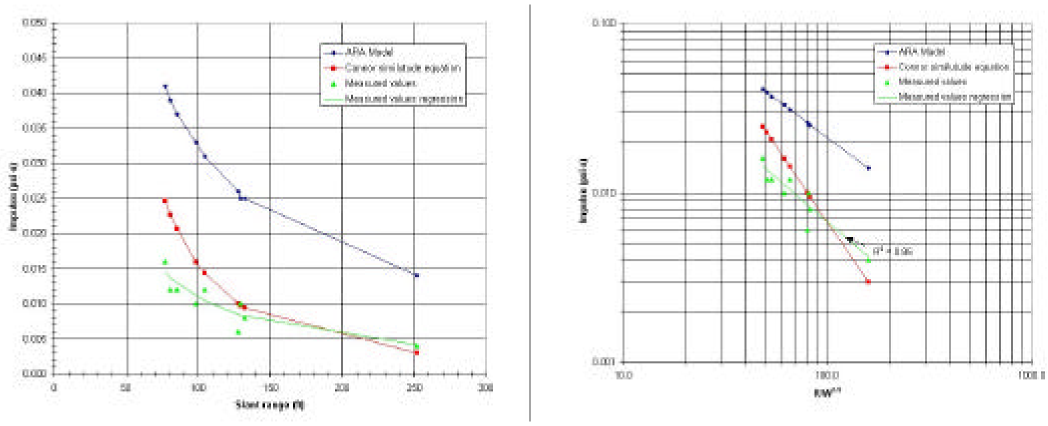


Figure B.5 – Impulse – 4.05 lbs engineered charge

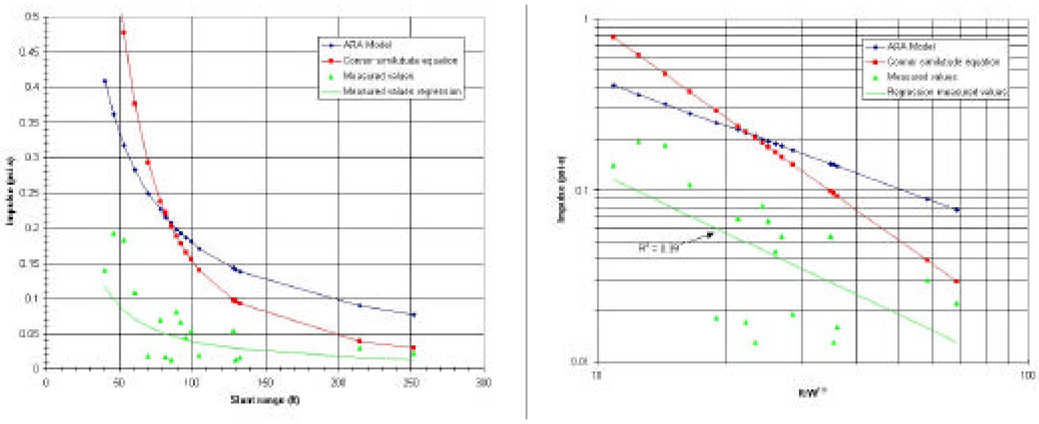


Figure B.6 – Impulse – Combined 50 lbs bulk charges data

Using linear regression, we computed the equations for the measured data from both types of charge with the least square method in an EXCEL® spreadsheet. The equation obtained for the 4.05 lbs engineered charge was:

$$I = 0.8952\left(R/W^{1/3}\right)^{-1.0535} \quad \text{or} \quad I/W^{1/3} = 0.5383\left(R/W^{1/3}\right)^{-1.0535} \qquad (5)$$

with a regression coefficient (R^2) of 0.85. This value of regression coefficient is better than what was obtained with the peak overpressure which can be explained by the smaller dispersion of the data as shown in the right side of Figure B.5. Using the data from both bulk 50 lbs bulk charges tested, the following equation was obtained:

$$I = 1.9908\left(R/W^{1/3}\right)^{-1.191} \quad \text{or} \quad I/W^{1/3} = 0.5404\left(R/W^{1/3}\right)^{-1.191} \qquad (6)$$

with a regression coefficient (R^2) of 0.39. Contrary to the peak overpressure, in this case the dispersion of the data obtained with the bulk charge for the impulse data about the regression curve is very large hence the small regression coefficient. Care should therefore be used to make conclusions based on this data.

Both charges experimental data as well as the Connor similitude equations and ARA model are illustrated in Figure B.7 below. Only the log-log graph of the data as a function of "$R/W^{1/3}$" was used.

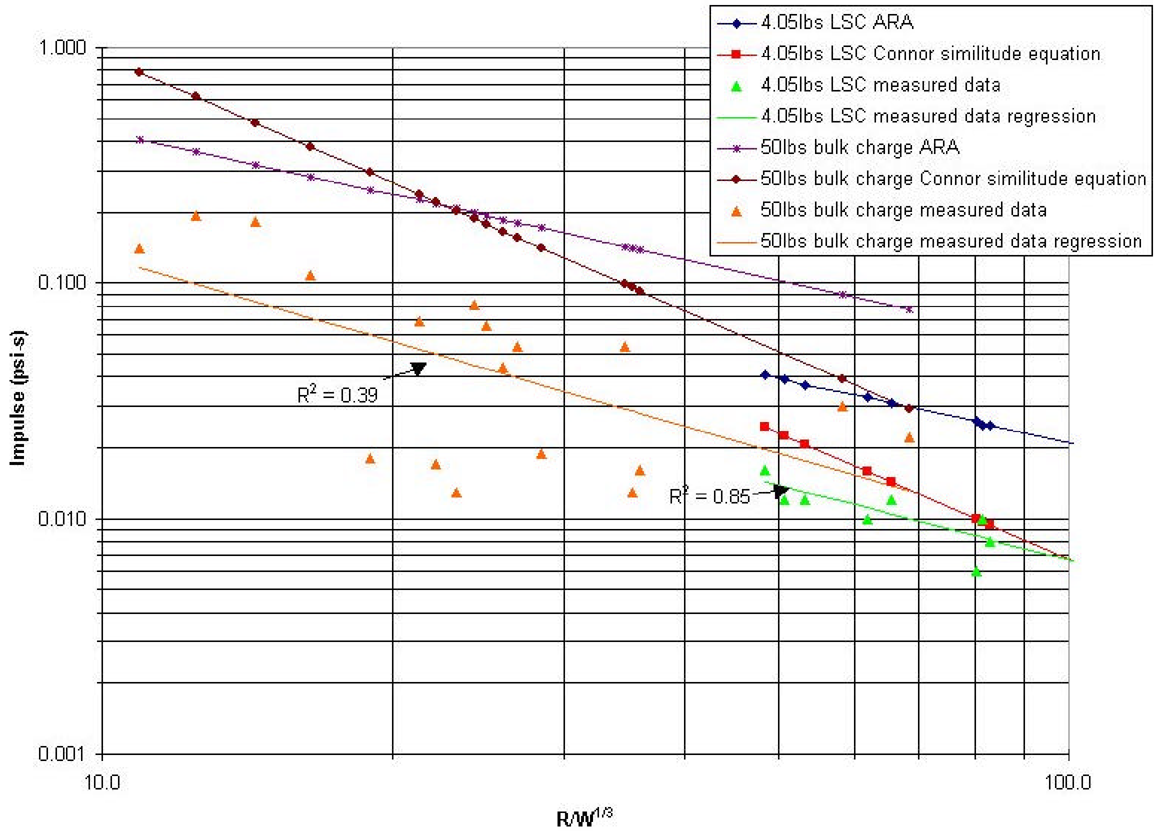


Figure B.7 - Impulse – data from both types of charges

It is interesting to note that for this value, the ARA model and the Connor similitude equations seem to match well for the bulk charges. The Connor similitude equation data were along the same line for the peak overpressure but this time this is not the case because of the $W^{1/3}$ factor.

Energy flux density

The energy flux density values computed by Sonalysts were compared to the values obtained from the ARA model and the Connor similitude equation presented as equation (2) above. The data obtained are given in Table B.3.

Table B.3 – Energy flux density data

Energy Flux Density (psi-in)					
Transducer	Slant range (ft)	Charge weight (lb)	ARA UWC	Connor Main Pile SimEQ	Field measure
Charge A (4.05lbs RDX engineered charge) – Pile 3					
A	77.2	4.05	0.586	0.101	0.132
B	80.9	4.05	0.531	0.087	0.097
C	85.1	4.05	0.478	0.074	0.055
D	98.6	4.05	0.352	0.047	0.038
F	104.5	4.05	0.312	0.039	0.054
G	127.7	4.05	0.206	0.021	0.013
H	129.6	4.05	0.199	0.020	0.057
I	132.3	4.05	0.191	0.019	0.054
L	251.6	4.05	0.050	0.002	0.004
Charge B (50lbs C4 bulk charge) – Pile 2					
A	77.2	50	9.314	3.045	0.813
B	80.9	50	8.449	2.697	0.138
C	85.1	50	7.605	2.305	0.078
D	98.6	50	5.599	1.463	0.419
F	104.5	50	4.961	1.221	0.105
G	127.7	50	3.269	0.656	0.280
H	129.6	50	3.170	0.626	0.047
I	132.3	50	3.037	0.589	0.082
L	251.6	50	0.798	0.079	0.051
Charge C (50lbs C4 bulk charge) – Pile 1					
A	40.3	50	24.539	3.589	4.168
B	46	50	16.219	5.526	2.996
C	53.1	50	10.349	4.353	2.094
D	60.6	50	6.844	1.756	1.506
F	69.7	50	4.417	0.162	1.062
G	89.3	50	2.034	1.009	0.573
H	92.1	50	1.846	0.678	0.530
I	95.8	50	1.632	0.259	0.480
L	214.7	50	0.131	0.090	0.064

The energy flux density data for Connor similitude equation was obtained using equation (2) above and the ARA model data was obtained using the EXCEL® spreadsheet calculator. As in the case of the peak overpressure and impulse, we prepared two types of graphs for each charge, one of the energy flux density as a function of the slant range using linear axis like Broussard and one with the data as a function of $R/W^{1/3}$ with log-log axis.

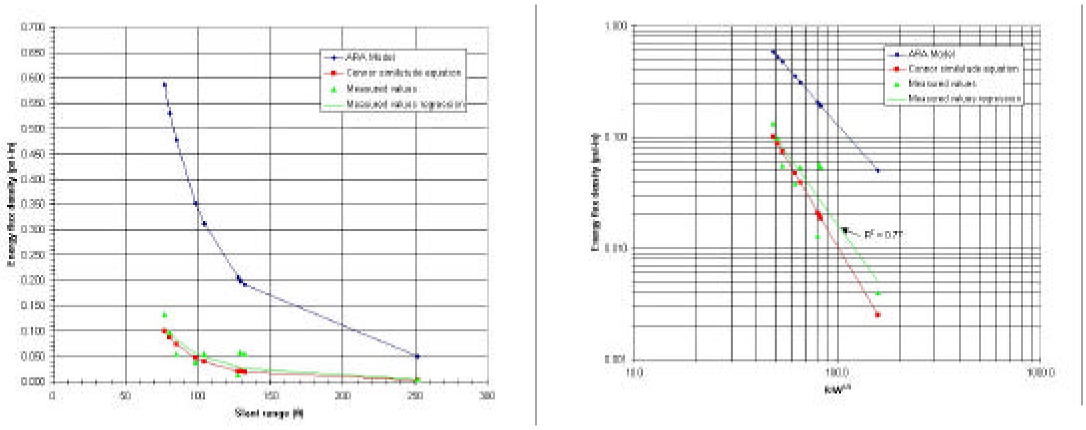


Figure B.8 – Energy flux density – 4.05 lbs engineered charge

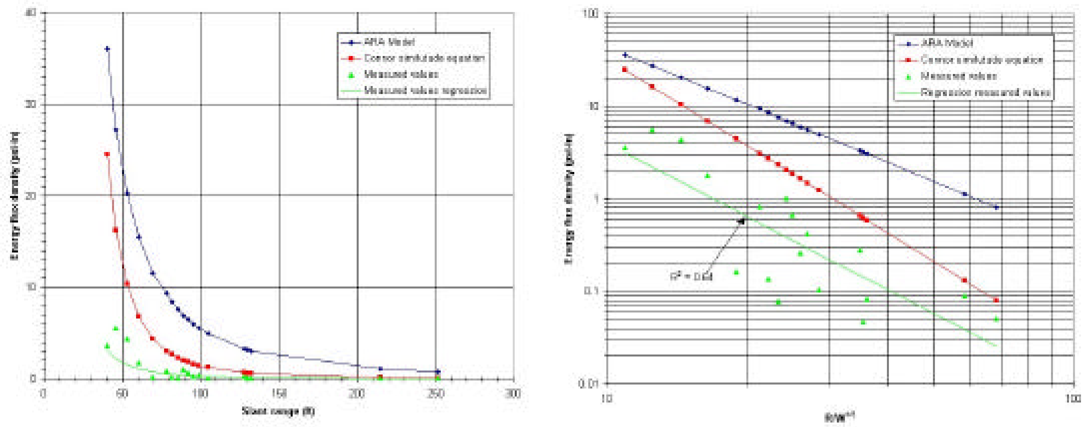


Figure B.9 – Energy flux density – Combined 50 lbs bulk charges data

Using linear regression, we computed the equations for the measured data from both types of charge with the least square method in an EXCEL® spreadsheet. The equation obtained for the 4.05 lbs engineered charge was:

$$E = 2390.6\left(R/W^{1/3}\right)^{-2.5840} \quad \text{or} \quad E/W^{1/3} = 1499.8\left(R/W^{1/3}\right)^{-2.5840} \qquad (7)$$

with a regression coefficient (R^2) of 0.77. This value of regression coefficient is close to what was obtained with the peak overpressure which can be explained by the dispersion of the data as shown in the right side of Figure B.8. Using the data from both bulk 50 lbs bulk charges tested, the following equation was obtained:

$$E = 1640.7\left(R/W^{1/3}\right)^{-2.6215} \quad \text{or} \quad E/W^{1/3} = 445.36\left(R/W^{1/3}\right)^{-2.6215} \qquad (8)$$

with a regression coefficient (R^2) of 0.64. Although better than the value obtained for the impulse data, this regression coefficient is still small. Care should therefore be used to make conclusions based on this data.

Both charges experimental data as well as the Connor similitude equations and ARA model are illustrated in Figure B.10 below. Only the log-log graph of the data as a function of "$R/W^{1/3}$" was used.

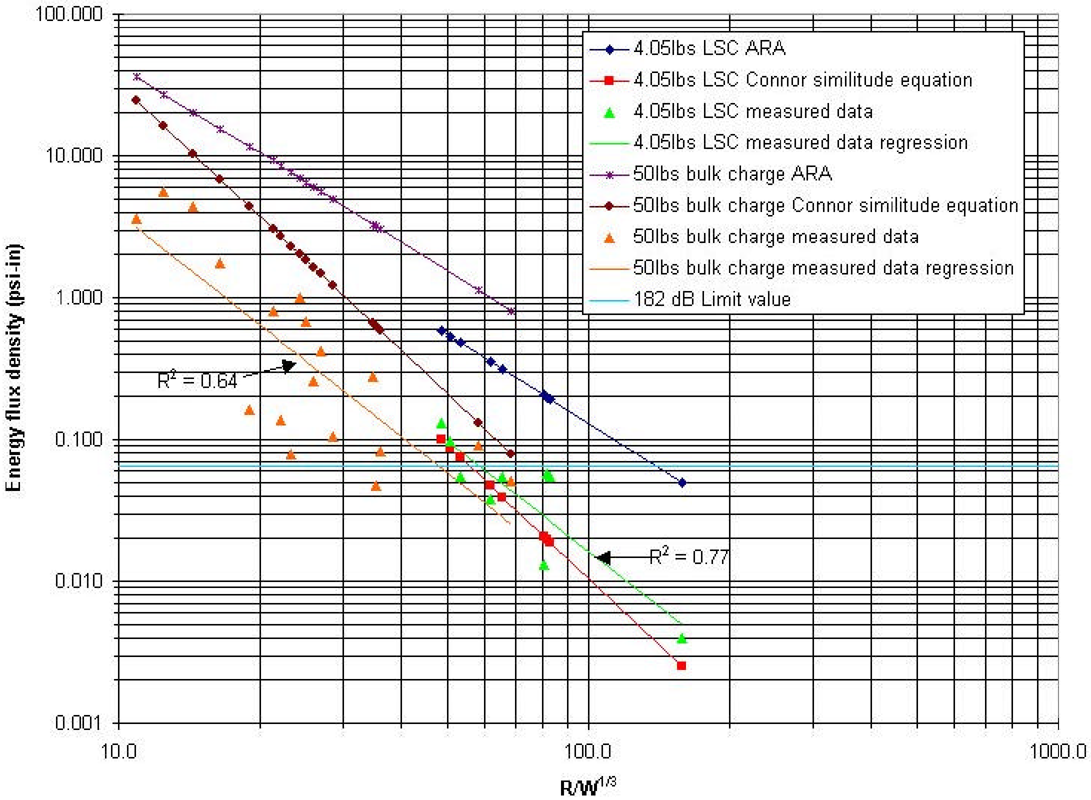


Figure B.10 – Energy flux density – data from both types of charges

The figure also presents the 182 dB (re 1 μPa^{2}sec) energy flux density criteria for marine mammal harassment as per NOAA 50 CFR Part 216. This value was converted in psi-in by using some assumptions of the ARA study that 182 dB (re 1 μPa^{2}sec) for any 1/3 octave band corresponds to 192.4 dB (re 1 μPa^{2}sec) of total energy flux density, which in turns corresponds to 0.06489 psi-in. From equations (7) and (8), the range distance corresponding to this value was computed for both charges. A value of 93.2 feet for the engineered charge and 176.1 feet for the bulk charge so a reduction factor of 1.89 is obtained when going from the bulk charge to the engineered charge.

Annex C

Corrections of Slant ranges & charge weights + Peak Overpressure sensors values review and analysis

Numerous calculations were done with the data collected from the experiment on structure # 97. Some of them included assumptions which are corrected here.

- The engineered LSC weight is 4.05lbs and not the 4.6 lbs used by Sonalyst
- The closest pile to the sensor array was severed with a bulk charge and not an engineered LSC.
- For the slant distance, the exact value was obtained as indicated below

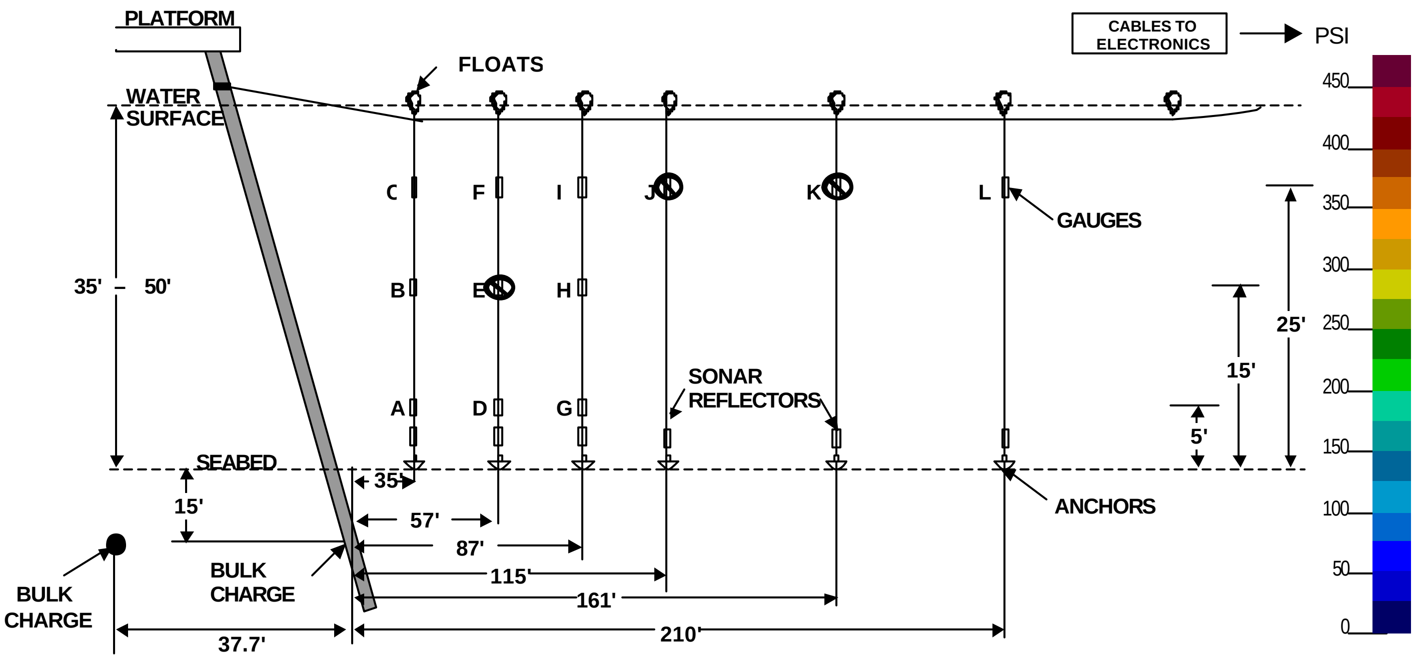


Figure C.1 - Sensor array deployment

Slant range distance for sensor A from the closest pile to the array (pile # 1) is obtained with vertical and horizontal distance of the sensor to the charge ; $(35\text{ft}^2 + 20\text{ft}^2)^{1/2}$.

The more distant piles (# 2 & 3) were at some angles from the closest pile and the array, so the real slant range distance for sensor A was obtained from $(74.6\text{ft}^2 + 20\text{ft}^2)^{1/2}$ and not $(72.7\text{ft}^2 + 20\text{ft}^2)^{1/2}$.

The slant range distances and charge weight were corrected in regard of each piles.

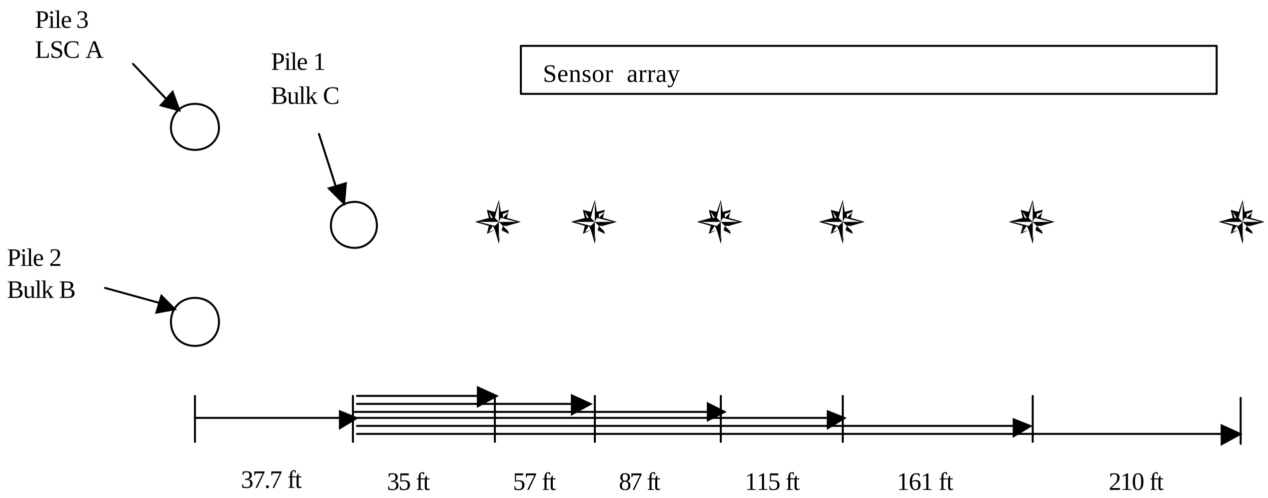


Figure C.2 - Top view of charges localization/piles and sensor array

These corrections permitted to establish the following table of measured data in regard of each piles.

Peak Overpressure (psi)		
Transducer	Slant range (ft)	Field measure (psi)
Charge A (4.05 lbs RDX engineered charge) Pile 3		
A___R35V5	77.2	139.2
B__R35V15	80.9	140.3
C__R35V25	85.1	78.8
D___R57V5	98.6	86.7
F__R57V25	104.5	74.4
G___R87V5	127.7	45.5
H__R87V15	129.6	93.2
I__R87V25	132.3	119
L_R210V25	251.6	10.1

Bulk Charge B (50 lbs C4) – Pile 2		
A___R35V5	77.2	137.9
B__R35V15	80.9	167.1
C__R35V25	85.1	98.2
D___R57V5	98.6	90.9
F__R57V25	104.5	134.2
G___R87V5	127.7	64.1
H__R87V15	129.6	82.7
I__R87V25	132.3	118.8
L_R210V25	251.6	26.8
Bulk Charge C (50 lbs C4) – Pile 1		
A___R35V5	40.3	244.1
B__R35V15	46	281.6
C__R35V25	53.1	279
D___R57V5	60.6	192.5
F__R57V25	69.7	211.6
G___R87V5	89.3	151.4
H__R87V15	92.1	137.7
I__R87V25	95.8	83.3
L_R210V25	214.7	41.2

Once these corrected values were established a comparison was done on the peak overpressure recorded in relation with the localization of the sensor. These comparisons are illustrated in the following sketch representing the recorded overpressure with colors.

The following figures show peak overpressure representations with the sensors locations.

The peak overpressures data obtained from the engineered linear shape charge showed some discrepancies illustrated in Figure C.3.

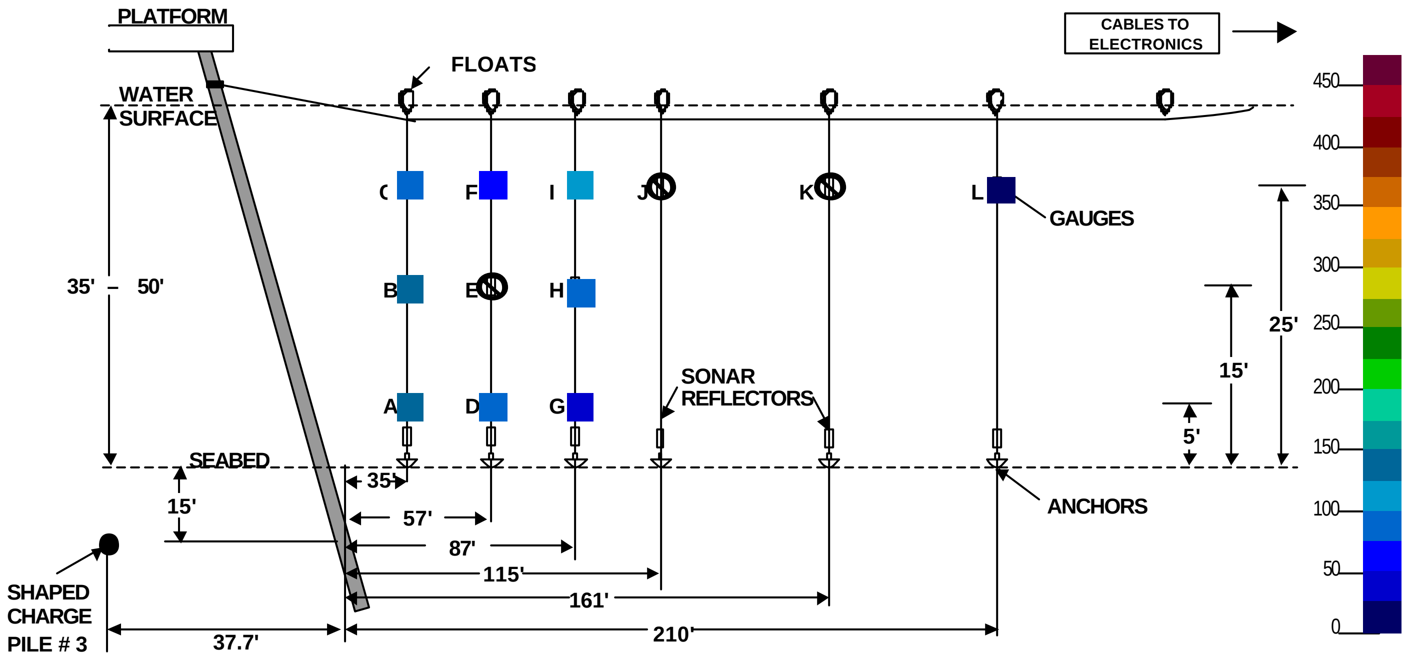


Figure C.3 - Peak overpressure measured values representation from LSC (A) in pile # 3

It would be logical, based on shock wave physics, to think that peak overpressure pattern should present higher readings closer to the source of the blast, but for the sensors F, G, H and I this logic was not respected. Sensor I which was further away from the blast than sensors F, H and G, 'saw' a higher value of peak overpressure compare to those three sensors. Value at sensor H was higher than at sensor G. These values are inconsistent with what is known from the physics of the experiment.

When we looked at the data obtained from the two bulk charges, some inconsistencies compared to the expected pattern were also observed. The bulk charge labeled # 1(more distant from the array) placed in pile # 2 showed some discrepancies illustrated in Figure C.4 below.

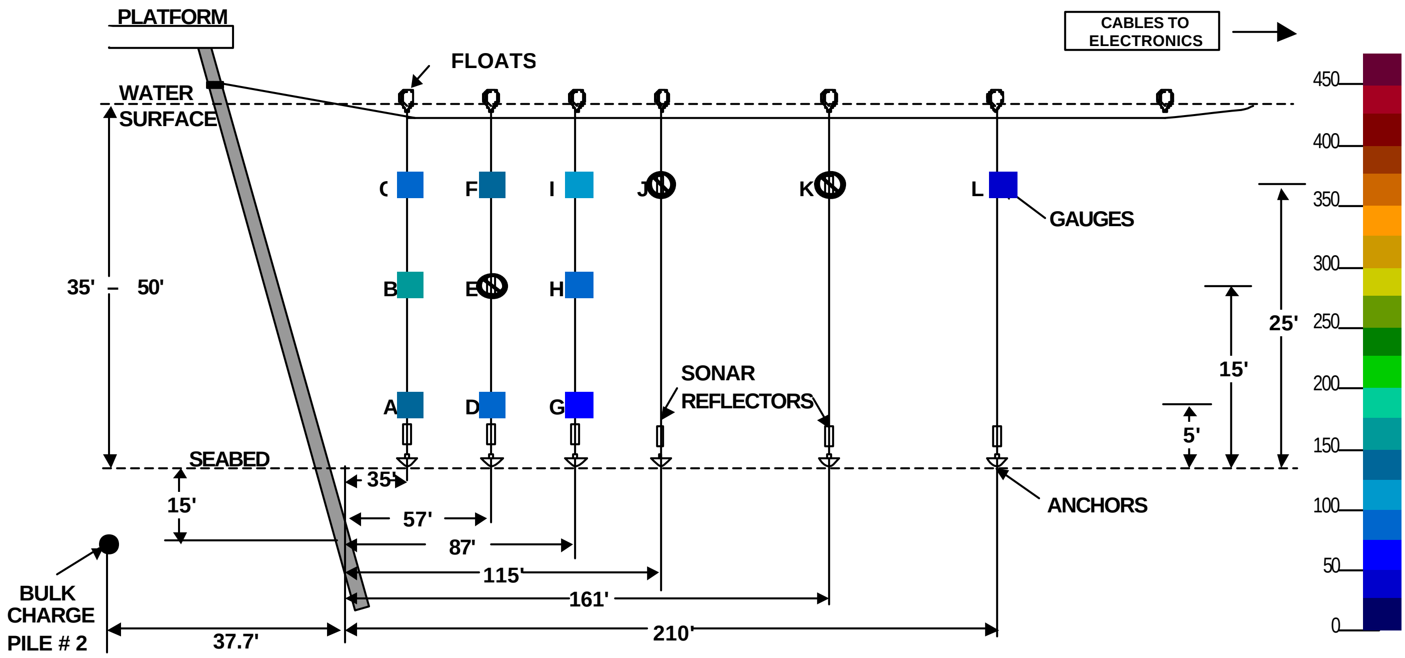


Figure C.4 - Peak overpressure measured values representation from bulk charge # 1(B) in pile # 2

As for the engineered linear shape charge, the peak overpressure pattern was expected to present higher readings closer to the source of the blast but, for most of the sensors, this logic was not respected. The value at sensor B was higher than value at sensor A. Sensor F peak pressure value was higher than sensors C and D. Sensor I was higher than sensor H and sensor H was higher than sensor G. As for the data recorded from the linear shape charge these values are inconsistent with what is known of the physics of the experiment.

The bulk charge labeled # 2 (closest to the array) placed in pile # 1 showed some others discrepancies but very few in comparison to the precedents and they are illustrated in Figure C.5.

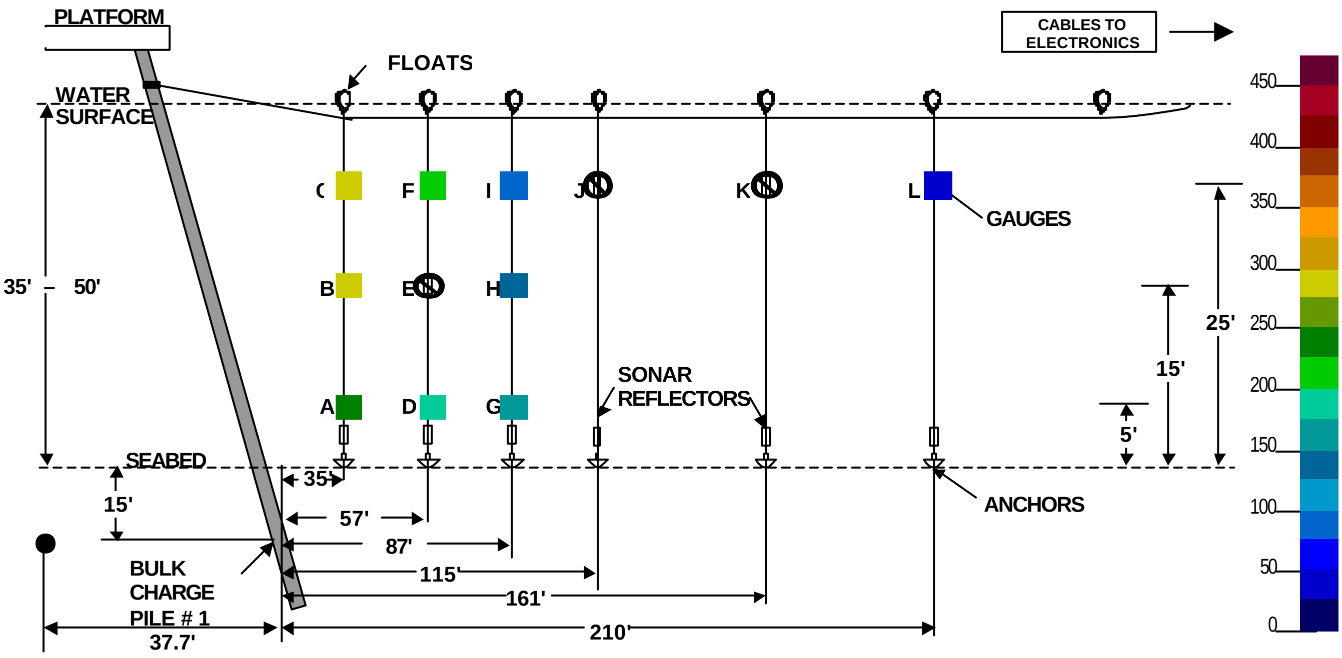


Figure C.5 - Peak overpressure measured values representation from bulk charge # 2(C) in pile # 1

As for the two preceding tests the peak overpressure pattern should present higher readings closer to the source of the blast, but for some of the sensors this logic was not respected. Value at sensors B and C was higher than value at sensor A. Sensor F was higher than sensor D. Still inconsistent with what is known of the physic of the experiment, it is however noticed there is less data outside of the logical pattern.

In summary, for the peak overpressure measurements from structure #97 three sensors (E, J, K) gave no readings. The readings of some sensors were hard to explain, example; readings for the engineered charge and the bulk charge # 1 from sensors G, H and I show the higher value at I, a smaller one at H and still a smaller one at G (sensor G was the closer to the blasts). In the same experiment the readings for bulk charge # 2 show the higher value at G, a smaller one at H and a still smaller one at I.

We cannot explain that two similar bulk charges which were detonated close one to the other in the same timing produced a completely reversed peak overpressure pattern on the same series of sensors.

Phenomenon of 'surface cutoff' and 'cavitation' (ref: Connor, J.G., *Underwater Blast Effects from Explosive Severance for Offshore Platform Legs and Well conductors*, Naval Surface Warfare Center, NAVSWC TR 90-532, 15 December 1990.) could eventually be a part of the explanation for the inconsistencies noted in relation to physics law.

An other possibility to consider would be the sensors reliability. Some tests could be designed to verify this reliability.